



# Defense Acquisition Research Journal

A Publication of the Defense Acquisition University

## TRANSITIONING to the Future

*Application of System and Integration Readiness  
Levels to Department of Defense Research  
and Development*  
**Sean Ross**

*Tailoring a Large Organization's Systems Engineering  
Process to Meet Project-Specific Needs*  
**Matthew Graviss, Shahram Sarkani, and  
Thomas A. Mazzuchi**

*Department of Defense Acquisition Program Termina-  
tions: Analysis of 11 Program Management Factors*  
**Lt Col Patrick Clowney, USAF (Ret.), Jason Dever, and  
Steven Stuban**

*Wartime Construction Project Outcomes as a  
Function of Contract Type*  
**Capt Ryan Hoff, USAF,  
Maj Gregory Hammond, USAF,  
Lt Col Peter Feng, USAF, and Edward White**

**The Defense Acquisition Professional Reading List**  
*Predator: The Secret Origins of the Drone  
Revolution*  
**Written by Richard Whittle**  
**Reviewed by Julien Demotes-Mainard**

# Article List

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## ARJ Extra



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# CONTENTS | Featured Research



p. **248**

## Application of System and Integration Readiness Levels to Department of Defense Research and Development

*Sean Ross*

Incorporates Technology, Integration, and Manufacturing Readiness Levels into a System Readiness Level metric. Provides a clear indicator to management for resource allocation during the technology maturation process and prevents premature system advancement.



p. **274**

## Tailoring a Large Organization's Systems Engineering Process to Meet Project-Specific Needs

*Matthew Graviss, Shahram Sarkani, and Thomas A. Mazzuchi*

Systems engineers must adhere to broad systems engineering policies, while tailoring processes for their projects. This article proposes a rule-based approach to streamline SE process tailoring.



p. **298**

## **Department of Defense Acquisition Program Terminations: Analysis of 11 Program Management Factors**

*Lt Col Patrick Clowney, USAF (Ret.),  
Jason Dever, and Steven Stuban*

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This article surveyed DoD acquisition program managers, DoD industry acquisition program managers, and DoD acquisition program management consultants to determine the program management factors that have the greatest influence on DoD program termination.



p. **331**

## **Wartime Construction Project Outcomes as a Function of Contract Type**

*Capt Ryan Hoff, USAF,  
Maj Gregory Hammond, USAF,  
Lt Col Peter Feng, USAF, and Edward White*

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Cost-plus-fixed-fee and firm-fixed-price construction had the same contract behaviors in wartime construction as in peacetime. Both structures exhibited similar risks and finished quality.



# CONTENTS | Featured Research

*p.* **vii**

**DAU Alumni Association**

---

*p.* **X**

**From the Chairman and Executive Editor**

---

*p.* **xii**

**Research Agenda 2016–2017**

---

*p.* **360**

**Professional Reading List**

---

*Predator: The Secret Origins of the Drone Revolution*

Written by Richard Whittle and reviewed by Julien Demotes-Mainard

*p.* **364**

**Defense ARJ Guidelines for Contributors**

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*p.* **369**

**Call for Authors**

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We are currently soliciting articles and subject matter experts for the 2016–2017 *Defense ARJ* print years.

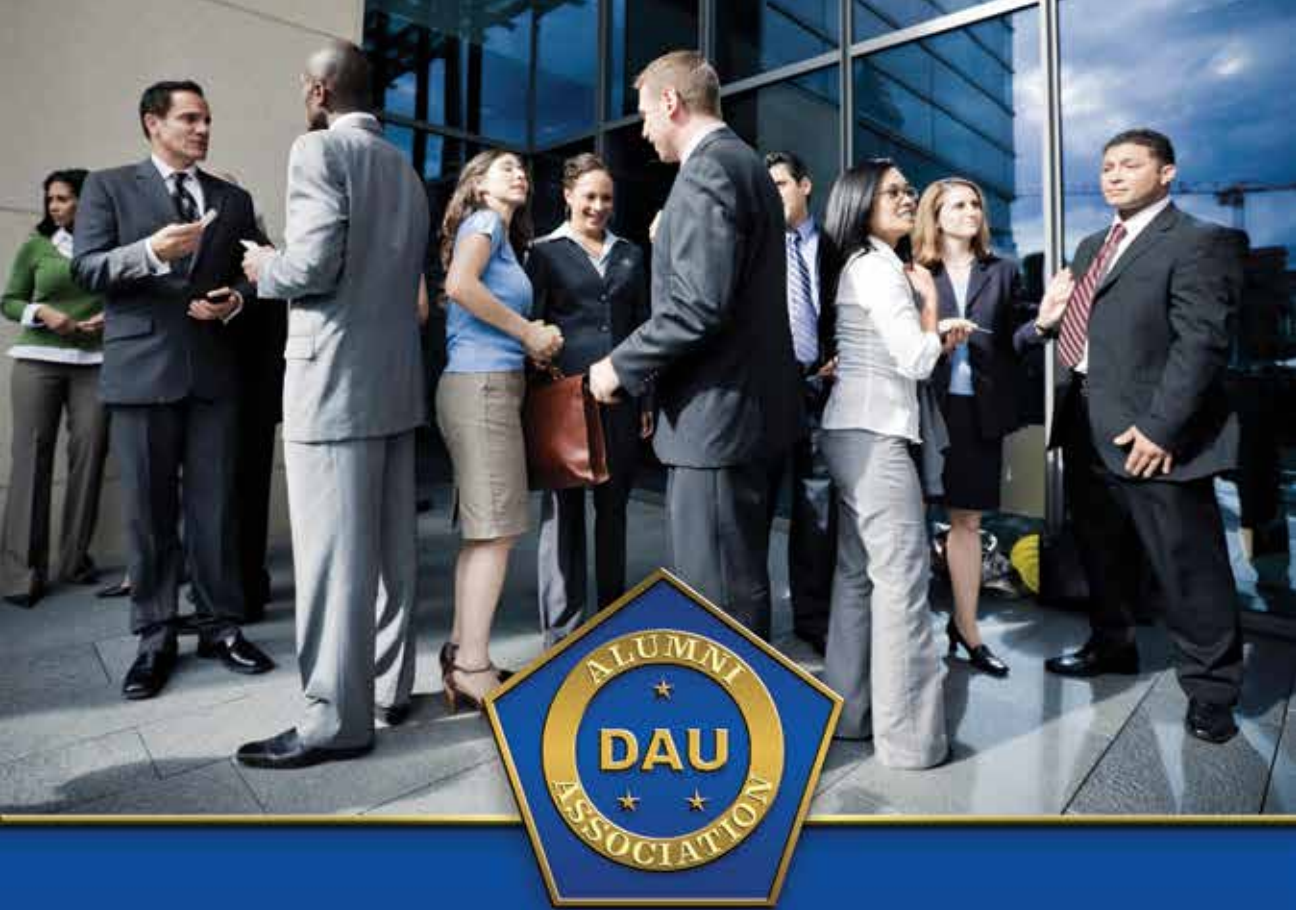
*p.* **372**

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- The competition is open to anyone interested in the DoD acquisition system and is not limited to government or contractor personnel.
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- First prize is \$1,000. Second prize is \$500.
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- Papers will be evaluated by a panel selected by the DAUAA Board of Directors and the DAU Director of Research.
- Award winners will present their papers at the DAU Acquisition Community Training Symposium, Tuesday, April 4, 2017, at the DAU Fort Belvoir campus.
- Papers must be submitted by December 16, 2016, and awards will be announced in January 2017.



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# FROM THE CHAIRMAN AND EXECUTIVE EDITOR

Dr. Larrie D. Ferreiro

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The theme for this edition of *Defense Acquisition Research Journal* is “Transitioning to the Future.” The first article, “Application of System and Integration Readiness Levels to Department of Defense Research and Development” by Sean Ross, demonstrates how to move beyond the Technology Readiness Level system of estimating technological maturity, which was developed by NASA in the 1980s. He shows how the modern paradigm

is to combine Technology, Integration, and Manufacturing Readiness Levels into a single metric—System Readiness Level—which can be used as a more robust indicator of the maturity of the technology transfer process.

“Tailoring a Large Organization’s Systems Engineering Process to Meet Project-Specific Needs” by Matthew Graviss, Shahram Sarkani, and Thomas A. Mazzuchi shows how a customized, streamlined approach to systems engineering can be performed using a rule-based process that allows project flexibility while also adhering to an organization’s top-level policies.

Patrick Clowney, Jason Dever, and Steven Stuban, in “Department of Defense Acquisition Program Terminations: Analysis of 11 Program Management Factors,” discuss the results of their surveys of acquisition program managers in the DoD, industry, and consultancies,

which evaluated the factors that have the greatest influence on DoD program termination, and how the viewpoints of these three groups differed or aligned.

Finally, “Wartime Construction Project Outcomes as a Function of Contract Type” by Ryan Hoff, Gregory Hammond, Peter Feng, and Edward White shows that in wartime contracting, although cost-plus-fixed-fee contracts exhibited greater cost and schedule growth than firm-fixed-price contracts, neither the finished quality nor the associated construction risks differed greatly between them.

The featured book in this issue’s Defense Acquisition Professional Reading List is *Predator: The Secret Origins of the Drone Revolution* by Richard Whittle, reviewed by Julien Demotes-Mainard at Avascent Europe.





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# DAU CENTER FOR DEFENSE ACQUISITION

## RESEARCH AGENDA 2016–2017

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This Research Agenda is intended to make researchers aware of the topics that are, or should be, of particular concern to the broader defense acquisition community within the federal government, academia, and defense industrial sectors. The center compiles the agenda annually, using inputs from subject matter experts across those sectors. Topics are periodically vetted and updated by the DAU Center's Research Advisory Board to ensure they address current areas of strategic interest.

The purpose of conducting research in these areas is to provide solid, empirically based findings to create a broad body of knowledge that can inform the development of policies, procedures, and processes in defense acquisition, and to help shape the thought leadership for the acquisition community. Most of these research topics were selected to support the DoD's Better Buying Power Initiative (see <http://bbp.dau.mil>). Some questions may cross topics and thus appear in multiple research areas.

Potential researchers are encouraged to contact the DAU Director of Research ([research@dau.mil](mailto:research@dau.mil)) to suggest additional research questions and topics. They are also encouraged to contact the listed Points of Contact (POC), who may be able to provide general guidance as to current areas of interest, potential sources of information, etc.

## **Competition POCs**

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- Frank Kenlon (global market outreach), DAU: frank.kenlon@dau.mil

## **Measuring the Effects of Competition**

- What means are there (or can be developed) to measure the effect on defense acquisition costs of maintaining the defense industrial base in various sectors?
- What means are there (or can be developed) of measuring the effect of utilizing defense industrial infrastructure for commercial manufacture, and in particular, in growth industries? In other words, can we measure the effect of using defense manufacturing to expand the buyer base?
- What means are there (or can be developed) to determine the degree of openness that exists in competitive awards?
- What are the different effects of the two best value source selection processes (trade-off vs. lowest price technically acceptable) on program cost, schedule, and performance?

## **Strategic Competition**

- Is there evidence that competition between system portfolios is an effective means of controlling price and costs?
- Does lack of competition automatically mean higher prices? For example, is there evidence that sole source can result in lower overall administrative costs at both the government and industry levels, to the effect of lowering total costs?
- What are the long-term historical trends for competition guidance and practice in defense acquisition policies and practices?



- To what extent are contracts being awarded non-competitively by congressional mandate for policy interest reasons? What is the effect on contract price and performance?
- What means are there (or can be developed) to determine the degree to which competitive program costs are negatively affected by laws and regulations such as the Berry Amendment, Buy America Act, etc.?
- The DoD should have enormous buying power and the ability to influence supplier prices. Is this the case? Examine the potential change in cost performance due to greater centralization of buying organizations or strategies.

### **Effects of Industrial Base**

- What are the effects on program cost, schedule, and performance of having more or fewer competitors? What measures are there to determine these effects?
- What means are there (or can be developed) to measure the breadth and depth of the industrial base in various sectors that go beyond simple head-count of providers?
- Has change in the defense industrial base resulted in actual change in output? How is that measured?

### **Competitive Contracting**

- Commercial industry often cultivates long-term, exclusive (noncompetitive) supply chain relationships. Does this model have any application to defense acquisition? Under what conditions/circumstances?
- What is the effect on program cost, schedule, and performance of awards based on varying levels of competition: (a) “Effective” competition (two or more offers); (b) “Ineffective” competition (only one offer received in response to competitive solicitation); (c) split awards vs. winner take all; and (d) sole source.

## **Improve DoD Outreach for Technology and Products from Global Markets**

- How have militaries in the past benefitted from global technology development?
- How/why have militaries missed the largest technological advances?
- What are the key areas that require the DoD's focus and attention in the coming years to maintain or enhance the technological advantage of its weapon systems and equipment?
- What types of efforts should the DoD consider pursuing to increase the breadth and depth of technology push efforts in DoD acquisition programs?
- How effectively are the DoD's global science and technology investments transitioned into DoD acquisition programs?
- Are the DoD's applied research and development (i.e., acquisition program) investments effectively pursuing and using sources of global technology to affordably meet current and future DoD acquisition program requirements? If not, what steps could the DoD take to improve its performance in these two areas?
- What are the strengths and weaknesses of the DoD's global defense technology investment approach as compared to the approaches used by other nations?
- What are the strengths and weaknesses of the DoD's global defense technology investment approach as compared to the approaches used by the private sector—both domestic and foreign entities (companies, universities, private-public partnerships, think tanks, etc.)?
- How does the DoD currently assess the relative benefits and risks associated with global versus U.S. sourcing of key technologies used in DoD acquisition programs? How could the DoD improve its policies and procedures in this area to enhance the benefits of global technology sourcing while minimizing potential risks?

- How could current DoD/U.S. Technology Security and Foreign Disclosure (TSFD) decision-making policies and processes be improved to help the DoD better balance the benefits and risks associated with potential global sourcing of key technologies used in current and future DoD acquisition programs?
- How do DoD primes and key subcontractors currently assess the relative benefits and risks associated with global versus U.S. sourcing of key technologies used in DoD acquisition programs? How could they improve their contractor policies and procedures in this area to enhance the benefits of global technology sourcing while minimizing potential risks?
- How could current U.S. Export Control System decision-making policies and processes be improved to help the DoD better balance the benefits and risks associated with potential global sourcing of key technologies used in current and future DoD acquisition programs?

### **Comparative Studies**

- Compare the industrial policies of military acquisition in different nations and the policy impacts on acquisition outcomes.
- Compare the cost and contract performance of highly regulated public utilities with nonregulated “natural monopolies,” e.g., military satellites, warship building, etc.
- Compare contracting/competition practices between the DoD and complex, custom-built commercial products (e.g., offshore oil platforms).
- Compare program cost performance in various market sectors: highly competitive (multiple offerors), limited (two or three offerors), monopoly?
- Compare the cost and contract performance of military acquisition programs in nations having single “purple” acquisition organizations with those having Service-level acquisition agencies.





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# Application of **System and Integration** **READINESS LEVELS** to Department of Defense **RESEARCH** and **DEVELOPMENT**

 **Sean Ross**

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Technology Readiness Level only tells part of the story of system maturation. As component technologies are developed to become part of systems, there are also integration and manufacturing issues to consider. This article improves upon the System and Integration Readiness Level concepts previously developed by B. J. Sauser et al., combines the concepts of Technology, Integration, and Manufacturing Readiness Levels, adapted for use in defense acquisition, into a single metric—System Readiness Level. This metric can then be used as an indicator to identify areas for resource allocation to enable the most efficient path to technology transition and to prevent premature system advancement.

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**Keywords:** *Technology Readiness Level (TRL), Integration Readiness Level (IRL), Manufacturing Readiness Level (MRL), System Readiness Level (SRL), interface development*





In an ideal world, a component technology would develop concurrently with its interfaces and its ability to be manufactured. In the real world, technologies lead both their interfaces and manufacturing infrastructure. For example, motorcycles were first made with fixed foot-pegs until some rather spectacular, spin-out wrecks occurred, prompting folding foot-pegs. The human-motorcycle interface maturity followed the technical maturity at the expense of safety. Early airplanes were made, one-at-a-time, with bicycle manufacturing equipment. The manufacturing maturity lagged the technology. The competing pitfall in system development is the premature advancement of a technology to the next level of development in advance of its interfaces, such as the current state of the F-35 program. Although the program is in late stage development, interface and component technology issues are still emerging that are preventing full operational capability (Bender, 2015). We can do a better job by minimizing the gap between interface, manufacturing, and technology maturity. Integration and system readiness are not yet implemented in any formal way Department of Defense (DoD)-wide.

This article explains a method to combine Technology Readiness Level (TRL) (See Appendix, Table A-1), Integration Readiness Level (IRL), and Manufacturing Readiness Level (MRL) (See Appendix, Table A-2) into a single metric—System Readiness Level (SRL)—that can provide guidance to decision makers during the technology maturation process. Such guidance can minimize the delays and mishaps likely to occur when interfaces and manufacturing significantly lag their component technologies.

## Background

The DoD Research, Development, Test and Evaluation budget is subdivided into seven separate activities: basic research; applied research; advanced technology development; advanced component development and prototypes; system development and demonstration; research, development, test and evaluation (RDT&E) management support; and operational systems development, i.e., the DoD categories of funding and technology development (Appendix, Table A-3). These seven activities are designated as DoD 6.1 through 6.7. This article incorporates the 6.1 through 6.7 levels of funding and appropriate levels of maturity so that the same metric can be used throughout the acquisition life cycle. Verbal definitions of TRL, MRL, IRL, and SRL are included at the end of the article.

Sauser, Ramirez-Marquez, and Devanandham, and Dimarzio (2007), and Sauser, Ramirez-Marquez, Magnaye, and Tan (2008a) furthered the concepts of TRL to include IRL and SRL (Sauser, Forbes, Long, & McGrory, 2009; Sauser, Gove, Forbes, & Ramirez-Marquez, 2010). These approaches emphasize that the interfaces between subsystems are every bit as important as the subsystems themselves, and that no system can be deemed ready for deployment based on the component technologies alone.

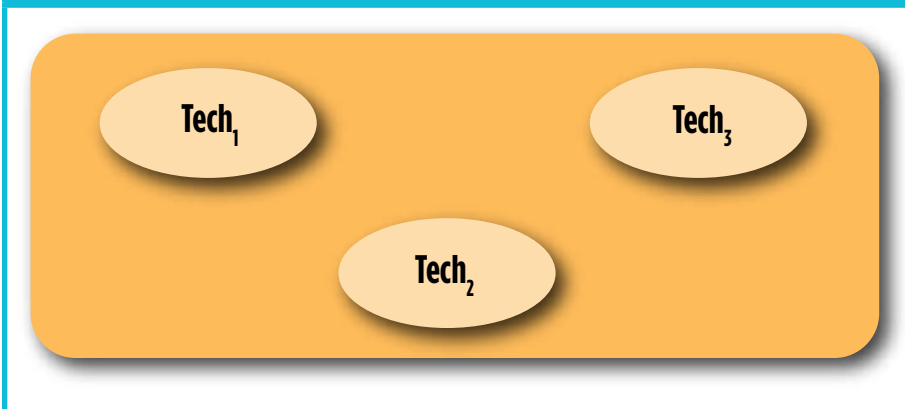
## Method

Sauser's basic approach is to imagine a system composed of component technologies from 1 to  $n$ , each with a TRL as shown in equation (1) and Figure 1.

$$TRL = trl_i = \{trl_1, trl_2, \dots, trl_n\} \quad (1)$$

*Mathematical Note.* A list of symbols or numbers in braces represents a vector. A subscripted symbol indicates one element out of a vector. A number without subscripts indicates the whole vector quantity. Lower case is used for normalized quantities.

**FIGURE 1. A SYSTEM AS A COLLECTION OF COMPONENT TECHNOLOGIES**



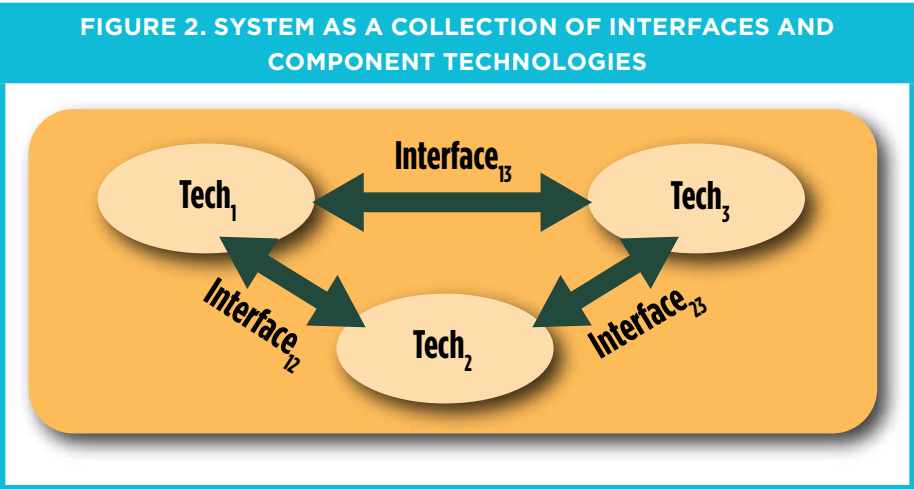
Note. (Sauser, 2008)

For example, a motorcycle can be viewed as an engine, power train, exhaust, electrical system, cooling system, saddle, suspension, wheels, gauges, steering, headlamp, etc.

Each component technology has a potential interface with each other component and with the external environment, including the possibility of an interface going both ways, as shown in equation (2). For simplicity, Figure 2 shows the interfaces with double arrows, as if  $irl_{12} = irl_{21}$ , which need not be the case. IRL must be expressed as a two-dimensional matrix rather than a one-dimensional vector. The vector is generally square—with the same number of rows and columns. The diagonal of the matrix is not used since a technology always works with itself.

$$IRL = irl_{ij} = \left\{ \begin{array}{cccc} x & irl_{12} & irl_{13} & \cdots & irl_{1n} \\ irl_{21} & x & irl_{21} & \cdots & irl_{2n} \\ irl_{n1} & irl_{n1} & irl_{n3} & \cdots & irl_{nn} \end{array} \right\}$$

(2)



In the Sauser approach, The IRL matrix and the TRL vector are multiplied together as a vector product (U.S. Navy, 2009, p. 35) to form an SRL vector that can be averaged for an overall SRL (Sauser, Verma, Ramirez-Marequez, Gove, 2006, p. A-12; Sauser et al., 2007, p. 681; U.S. Navy, 2009, p. 33). Note that this paper shows matrix notation in both reduced tensor notation and matrix notation as a convenience for a multidisciplinary audience.  $SRL_j$ ,  $[SRL]$  and  $\overrightarrow{SRL}$  all refer to the same vector entity and all versions of equation

(3) show the same tensor/matrix operation in different notation. Equation (4) shows the Sauser formula for SRL. Computational and practical examples of all formulas will be shown in the examples section.

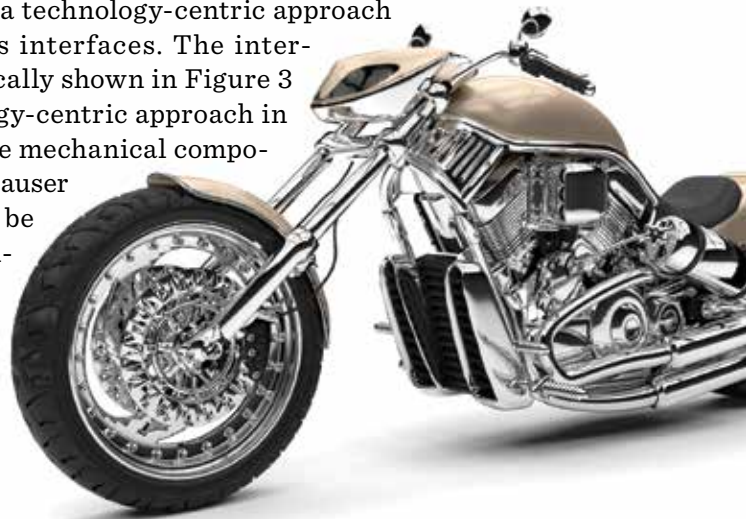
$$SRL_j = IRL_{ij} TRL^i = IRL_{1j} TRL^1 + IRL_{2j} TRL^2 + \dots + IRL_{nj} TRL^n \quad (3a)$$

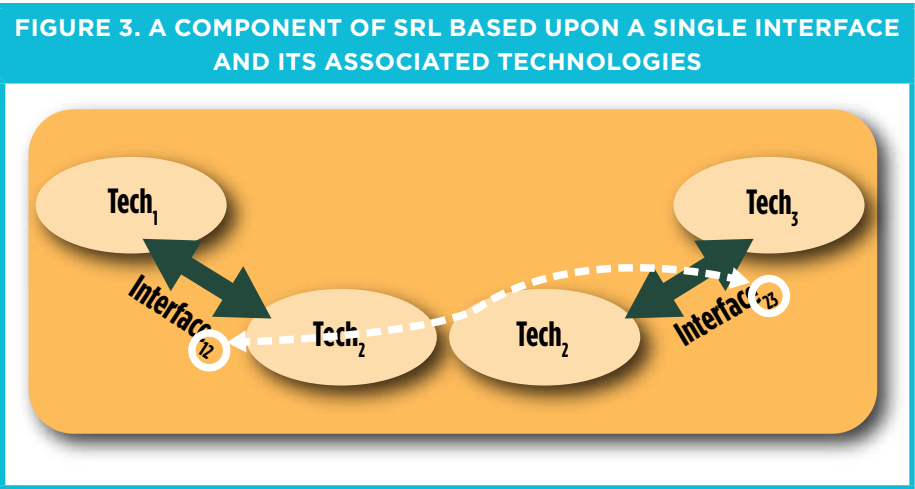
$$[SRL] = \begin{bmatrix} SRL_1 \\ SRL_2 \\ \dots \\ SRL_3 \end{bmatrix} = \begin{bmatrix} IRL_{11} TRL_1 + IRL_{12} TRL_2 + \dots + IRL_{1n} TRL_n \\ IRL_{21} TRL_1 + IRL_{22} TRL_2 + \dots + IRL_{2n} TRL_n \\ \dots \\ IRL_{n1} TRL_1 + IRL_{n2} TRL_2 + \dots + IRL_{nn} TRL_n \end{bmatrix} \quad (3b)$$

$$\overrightarrow{SRL} = \begin{Bmatrix} irl_{11} & irl_{12} & irl_{13} & \dots & irl_{1n} \\ irl_{12} & irl_{22} & irl_{21} & \dots & irl_{2n} \\ irl_{13} & irl_{21} & irl_{33} & \dots & irl_{3n} \end{Bmatrix} \begin{Bmatrix} trl_1 \\ trl_2 \\ trl_3 \end{Bmatrix} \quad (3c)$$

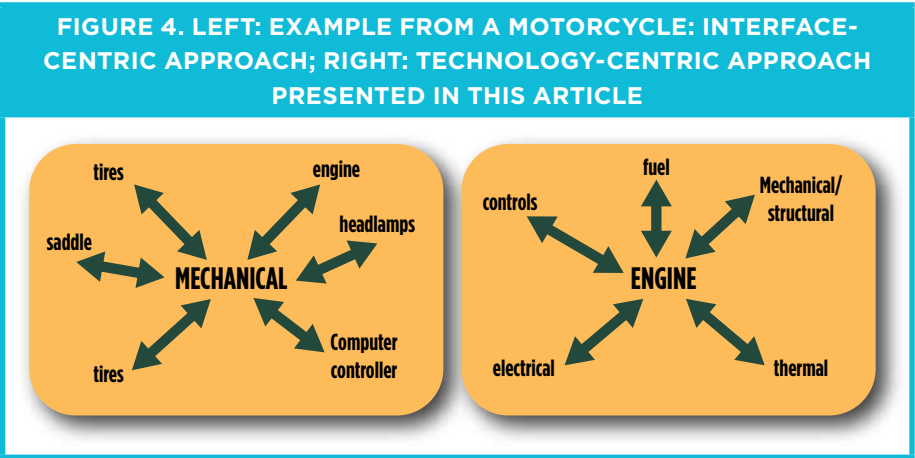
$$SRL = \frac{1}{N} \sum_{j=1 \text{ to } N} srl_j \quad (4)$$

As shown in equations (3a) and (3b), the Sauser mathematics views a component of SRL ( $SRL_i$ ) as being based upon a single interface type and its associated technologies; the  $SRL_1$  component includes  $TRL_1$ ,  $TRL_2$ , etc., and all of the  $IRL_{1n}$  rather than a technology-centric approach that included  $TRL_1$  with all its interfaces. The interface-centric approach is graphically shown in Figure 3 and contrasted with a technology-centric approach in Figure 4 using a motorcycle. The mechanical component of SRL ( $SRL_{\text{mechanical}}$ ) in the Sauser approach for a motorcycle would be based upon the mechanical-engine, mechanical-headlamps, mechanical-saddle, mechanical-tires, etc., interfaces. The interface-centric approach has some serious limitations as will be covered in the next sections.





Note. (Sauser et al., 2007)



Note. Left: (Sauser, 2008). Right: Ross, S. (2016). Application of System and Integration Readiness Levels to Department of Defense Research and Development. *Defense Acquisition Research Journal*, 23(3), In Print.

The average of the SRL vector, equation (4), describes how mature the system is. The Sauser approach may make sense for a single mission or project, such as the deployment of a new software system. However, it has some serious drawbacks for use in research and development where planners need to decide what technologies to develop for the eventual deployment of a new platform, weapon, or system. First, SRL, as defined in the U.S. Navy’s *Littoral Combat Ship Mission Module Program System Maturity Assessment Guide* (2009), is *interface-centric* as opposed to *component-centric*. The Sauser definition shows each interface with its associated technologies

rather than each technology with its associated interfaces. Second, SRL as defined by Sauser, has no clear meaning assigned to a given numerical value. In one presentation (Sauser, Ramirez-Marquez, Magnaye, & Tan, 2008b), SRL is defined along a value from 0 to 1 with five unequal intermediate levels and no verbal definitions akin to those for TRL, IRL, and MRL. This gives SRL a different kind of scale than IRL and TRL, which are clearly defined such that 1 is a concept and 9 is full deployment. Third, the Sauser-defined SRL only has meaning at the full system level. The interface-centric components of the SRL vector give no guidance to component developers. Finally, the definitions of IRL tend to be information technology (IT)-centric, emphasizing control and information. IRL needs to be applicable to a wide variety of interfaces, including mechanical, thermal, electrical, structural, and control interfaces as well as logistics, policy, and other ‘-ility’ and mission interfaces.

### Characteristics of a Useful System Readiness Level Metric

A useful metric will be defined so as to give a clear indication for planning resource allocation. SRL and IRL, as metrics, can be useful if they are defined correctly. The author proposes the following criteria for a useful SRL and IRL metric.

1. IRL definitions should be applicable to a wide variety of technologies.
2. SRL should be defined such that SRL=1 is a concept and SRL=9 is a mature, deployed system on the same basic scale as TRL, MRL, and IRL.
3. SRL should equal TRL when the interfaces are developed concurrently with the components, and should be less than TRL when interfaces are less mature than the components. This will give planners a clear metric that lets them know that it is time to transition funding into more interface-centric development or to proceed with component technology maturation.
4. SRL should be *technology-* or *component-*centric, not *interface-*centric. This makes it clear when a particular subcomponent is not able to progress further toward implementation due to an interface or manufacturing issue.
5. SRL should include MRL, TRL, and IRL.



6. SRL should be applicable to a wide variety of technical maturities (see Appendix, Table A-3), including basic research (6.1 funding); applied research (6.2 funding); advanced technology development (6.3 funding); advanced component development and prototypes (6.4 funding); system development and demonstration (6.5 funding); and operational systems development (6.7 funding), i.e., the DoD categories of funding and technology development. Note that 6.6 funding is not included because it is for management activities and not tied to a level of technical maturity.
7. SRL must be defined in such a way as to avoid maturity in one component overshadowing immaturity in another (Kujawski, 2010) and giving the illusion that the system is ready to progress. This implies that SRL should never be able to be greater than TRL at either the system or component level.

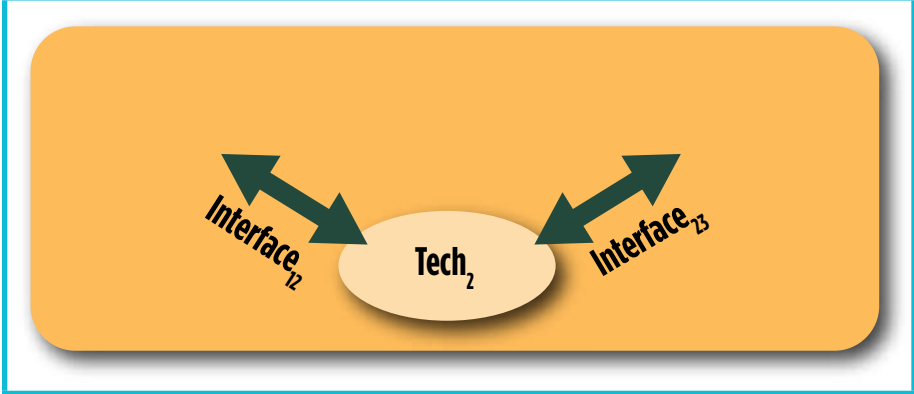
### Proposed System Readiness Level Metric

The author proposes that a more useful way to arrange MRL, TRL, and IRL is as a series of normalized dot products, rather than vector products (Sausser et al., 2008a, p. 47). This changes the view of the components of SRL from being interface-centric to being technology-centric, as shown in the contrast between Figure 3 and Figure 5, and between the right and left sides of Figure 4. The SRL components are equal to the product of the

normalized MRL, the TRL, and the mean of the normalized IRL, as shown in Table 1. In the notation that follows, upper case is reserved for standard (i.e., verbal) definitions and lower case is for normalized quantities. Note that the word ‘system’ in this article refers to a generic system—anything that can be usefully viewed as being composed of parts, rather than specifically as a deployed military asset. Likewise, the term ‘component’ refers to the parts that make up a larger grouping rather than exclusively as a line-replaceable item with a specific part number. The term interface should be viewed in the broad sense of the word to also include the external environment—the ‘ilities’ (availability, maintainability, vulnerability, reliability, supportability, etc.) and the DOTmLPF-P (Doctrine, Organization, Training, materiel, Leadership and Education, Personnel, Facilities-Policy).



FIGURE 5. A COMPONENT OF SRL BASED UPON A SINGLE TECHNOLOGY AND ITS INTERFACES



Note. Ross, S., (2016). Application of System and Integration Readiness Levels to Department of Defense Research and Development. *Defense Acquisition Research Journal*, 23(3), In Print.

TABLE 1. NORMALIZED INTEGRATION READINESS LEVEL DEFINITIONS

IRL =	Integration readiness level scalar						
IRL <sub>jk</sub> =	IRL for the interface between technology j and technology k						
irl <sub>jk</sub> =	normalized IRL for interface between technology j and technology k						
irl <sub>jj</sub> =	1, the interface always works with itself						
irl <sub>jk</sub> =	irl <sub>kj</sub> , the interface works both ways. It may be useful for some systems to break the IRL apart into two components. For purposes of this article, the author assumes that if the motor-fuel interface works, so does the fuel-motor interface.						
irl =	IRL/i*						
<b>Research level</b>	6.1	6.2	6.3	6.4	6.5	6.6	6.7
<b>i*</b>	1	2	3	5	6	7	9

$$\overline{irl}_i = mean[irl_{ij}] \frac{1}{n} \sum_{j=1}^n irl_{ij}$$

To have SRL equal to TRL when IRL and MRL are at commensurate levels of development requires normalized versions of IRL and MRL scaled to the level of research. Basic research (6.1 funding) should have a goal of an IRL of 1 (Interface identification) and MRL of 2 (Manufacturing concepts

identified), so that the normalized *mrl* and *irl* equal 1 when the appropriate levels of IRL and MRL are reached. Likewise, system development and demonstration (6.5 funding) should have as its goal an IRL of 6 (interface control) and an MRL of 6 (prototype in a production-relevant environment) so the normalized *mrl* and *irl* equal 1 when the appropriate levels are reached. The signal to proceed to the next step in system development occurs when SRL equals TRL, indicating that the interfaces and manufacturing base are at a commensurate level of development with the component technologies. The nomenclature and definitions for normalized IRL are shown in Table 1. The normalization factors are chosen to be consistent with the funding categories listed in the DoD Research, Development, Test and Evaluation (RDT&E) budget (Appendix, Table A-3). Different communities may have differing levels of MRL, TRL, and IRL goals vs. acquisition stage so that the normalization factors are intended as starting suggestions. It would also be viable to have normalization factors based on the DoD 5000.02 Model 1 (DoD, 2015).

The normalized IRLs associated with a particular technology need to be averaged to come up with a representative number indicating how well that particular technology relates to the other subsystems or technologies in the system. The  $\overline{irl}_i$  accomplish this. Note that the normalization factors ‘reset’ the metric at each level of maturity, which reduces the possibility of one very mature component masking a less mature one in the metric. MRL normalizations and definitions are shown in Table 2. Note that the normalized MRL (*mrl*) does not replace the existing MRL, but is an intermediate step needed for SRL calculation as is the normalized IRL (*irl*).

TABLE 2. NORMALIZED MANUFACTURING READINESS LEVEL DEFINITIONS							
$MRL_j =$		MRL for technology j					
$mrl_j =$		normalized MRL for technology j					
$mrl_j =$		$MRL_j/m^*$					
<b>Research level</b>	6.1	6.2	6.3	6.4	6.5	6.6	6.7
<b>m*</b>	2	3	4	5	6	8	10

The SRL metric is formed by multiplying the normalized MRL, the TRL, and the mean of the normalized IRL in a scalar contraction (dot product) such that each component  $SRL_i$  has a value from 1 to TRL as does the scalar SRL. System readiness definitions and nomenclature are shown in Table 3.

TABLE 3. SYSTEM READINESS LEVEL DEFINITIONS AND NOMENCLATURE

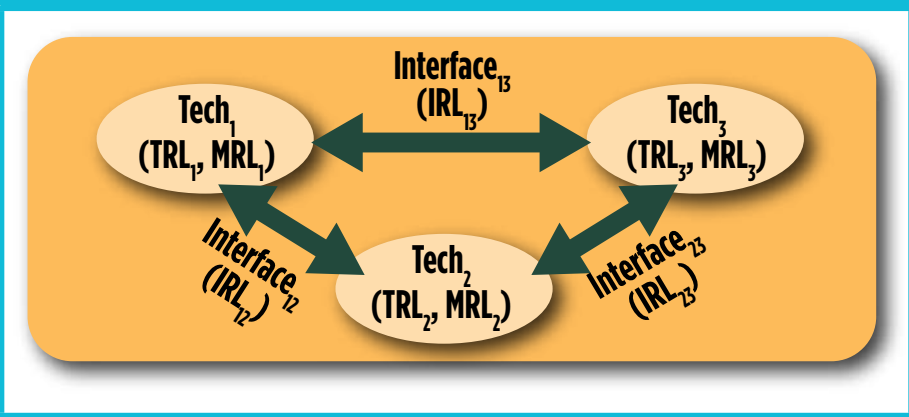
SRL =	System readiness level scalar, the mean of the system readiness levels for all component technologies
SRL <sub>j</sub> =	System readiness level for component j

$$SRL_i = mrl_i TRL_i \overline{irl}_i$$
$$SRL = mean[\{mrl_1 mrl_2 \dots mrl_n\} \cdot \{TRL_1 TRL_2 \dots TRL_n\} \cdot \{\overline{irl}_1 \overline{irl}_2 \dots \overline{irl}_n\}]$$

Numerical Examples

For simplicity and clarity, this article shows three numerical-only examples using a hypothetical system with three technologies, as shown in Figure 6.

FIGURE 6. EXAMPLE SYSTEM WITH THREE COMPONENT TECHNOLOGIES



Each technology has an associated TRL and MRL. Each Interface has an associated IRL. Notationally, this will be of the form shown in equations (6), (7), and (8).

$$TRL_i = \{TRL_1, TRL_2, TRL_3\} \tag{6}$$

$$MRL_i = \{MRL_1, MRL_2, MRL_3\}. \tag{7}$$

$$IRL_{ij} = \left\{ \begin{array}{ccc} X & IRL_{12} & IRL_{13} \\ X & X & IRL_{23} \\ X & X & X \end{array} \right\} \quad (8)$$

### Early Technology with Adequate Interfaces

The author assumes a simple, three-component system, with components 1, 2, and 3 funded at the 6.2—applied research level—using the following values for MRL, TRL, and IRL shown in equations (9), (10), (11), and (12).

$$MRL_i = \{2, 3, 3\} \quad (9)$$

$$TRL_i = \{3, 2, 4\} \quad (10)$$

$$\overline{TRL} = mean[3, 2, 4] = 3 \quad (11)$$

$$IRL_{ij} = \left\{ \begin{array}{ccc} X & IRL_{12} & IRL_{13} = 2 \\ X & X & IRL_{23} = 2 \\ X & X & X \end{array} \right\} \quad (12)$$

The first step is to calculate the normalized *mrl* and *irl* using the equations from Tables 1 and 2. Because this is 6.2 funded, the *m\** normalization factor is 3 from Table 2, indicating that we expect 6.2 funded technologies to be at an MRL of 3 before progressing. Likewise, the *i\** normalization factor is 2 from Table 1. Normalized values are shown in equations (13), (14), and (15).

$$mrl_i = MRL_i / m^* = \{2, 3, 3\} / 3 = \{0.66, 1, 1\} \quad (13)$$

$$irl_{ij} = IRL_{ij} / 2 = \left\{ \begin{array}{ccc} X & 0.5 & 1 \\ X & X & 1 \\ X & X & X \end{array} \right\} \quad (14)$$

$$\begin{aligned} \overline{irl}_1 = \text{mean}[irl_{12}, irl_{13}] = 0.75, \overline{irl}_2 = \text{mean}[irl_{12}, irl_{23}] = 0.75, \overline{irl}_3 = \\ \text{mean}[irl_{23}, irl_{13}] = 1. \end{aligned} \quad (15)$$

The SRL vector is calculated from the products of the normalized  $mrl$ , average normalized  $irl$ , and TRL vectors using the formulas from Table 3, shown in equations (16) and (17).

$$SRL_i = mrl_i TRL_i \overline{irl}_i = \{0.66*3*0.75, 1*2*0.75, 1*4*1\} = \{1.49, 1.5, 4\} \quad (16)$$

$$SRL = \text{mean}[SRL_i] = 2.33 \quad (17)$$

## Analysis

$SRL = 2.33$  while the average TRL is 3, indicating a slight lag in at least one interface. From the normalized MRL, one can conclude that the system is at a mostly appropriate level of manufacturing readiness with two components at an  $mrl$  of 1 and one at 0.66.  $SRL_1$  and  $SRL_2$  are at 1.5, slightly lagging behind the technology readiness of 2 and 3 due to some interface development that needs to occur.  $SRL_3 = TRL_3 = 4$  indicates that this technology is at an appropriate level of interface and manufacturing readiness. The metric indicates to management that it is time to devote additional resources to the interfaces of technologies 1 and 2 before pushing ahead in further component or system development.

It is very important to conduct the early phases of interface readiness, which involve subject matter experts from different fields exchanging information and ensuring that there exists an interface solution. If this is skipped, then at the demonstration and prototyping levels of 6.4 research, many technology choices must be revisited because the technologies have matured separately and are becoming incompatible. Revisiting technology choices may then result in program delays, cost overruns, or mad scrambles to prepare for demonstrations or program cancellations. The classic case of this is thermal management, when a new technology



becomes available with thermal management as an afterthought, and the legacy platform for which it is intended becomes overwhelmed with the new thermal load. The thermal issues associated with 5th generation aircraft (Majumdar & Kjelgaard, 2015) are a result of thermal interface as an afterthought. The opposite appears to be happening in the semiconductor industry in which thermal management is a very active area of research in anticipation of higher thermal loads on microchips in the near future.

### Mid-level Technology with Lagging Interfaces

In a more abbreviated form than the previous example, we assume a simple, three-component system with components 1, 2, 3 funded at the 6.4 – demonstration level.  $MRL_i = \{3, 5, 5\}$ ;  $TRL_i = \{6, 4, 5\}$ ;  $\overline{TRL} = 5$ , and the IRL has the following values:  $IRL_{12} = 3$ ,  $IRL_{13} = 2$ , and  $IRL_{23} = 2$ . The SRL calculation is as follows:

$$mrl_i = \{0.6, 1, 1\}. \quad irl_{12} = 3/5, \quad irl_{13} = 2/5, \quad \text{and} \quad irl_{23} = 2/5, \quad \overline{irl}_1 = \text{mean}[irl_{12}, irl_{13}] = 0.5, \quad \overline{irl}_2 = \text{mean}[irl_{12}, irl_{23}] = 0.5, \quad \overline{irl}_3 = \text{mean}[irl_{23}, irl_{13}] = 0.4.$$

$$SRL_i = mrl_i \cdot TRL_i \cdot \overline{irl}_i = \{0.6 \cdot 6 \cdot 0.5, 1 \cdot 4 \cdot 0.5, 1 \cdot 5 \cdot 0.4\} = \{1.8, 2, 2\}$$

$$SRL = \text{mean}[SRL_i] = 1.3$$

***It makes no sense to continue and pursue more mature technology that may or may not work in the intended environment or with the other subsystems.***

### Analysis

The fact that  $SRL = 1.3$ , but there are TRLs at 6 and 4 and an average TRL of 5, alerts management there are serious manufacturing and interface issues, probably due to neglect in early technical development. Note that the  $mrl_i$  is 0.6 and is slightly lower than the other two; the  $SRL_i$  are very nearly all at 2; and the  $TRL_i$  are quite high—at 6, 4, and 5—due to the  $irl$  being much lower. This alerts management that emphasis needs to be placed on developing interfaces. Further component maturation is very risky and very likely counter-productive. It makes no sense to continue and pursue more mature technology that may or may not work in the intended environment or with the other subsystems. This system is headed toward program-killing safety, thermal, control, electrical, or other integration and deployment issues.



### Advanced Technology with One Lagging Interface

The author assumes a simple, three-component system, with components 1, 2, and 3 funded at the 6.7 — operational systems development level.  $MRL_i = \{7, 7, 7\}$ ;  $TRL_i = \{7, 7, 7\}$  and the IRL has the following values:  $IRL_{12} = 7$ ,  $IRL_{13} = 7$ , and  $IRL_{23} = 4$ . The SRL calculations are as follows:

$$mrl_i = \{1, 1, 1\}, \bar{irl}_{12} = 1, \bar{irl}_{13} = 1, \text{ and } \bar{irl}_{23} = 0.57, \bar{irl}_1 = \text{mean}[\bar{irl}_{12}, \bar{irl}_{13}] = 1, \bar{irl}_2 = \text{mean}[\bar{irl}_{12}, \bar{irl}_{23}] = 0.79, \text{ and } \bar{irl}_3 = \text{mean}[\bar{irl}_{23}, \bar{irl}_{13}] = 0.79.$$

$$SRL_i = mrl_i \cdot TRL_i \cdot \bar{irl}_i = \{1 \cdot 7 \cdot 1, 1 \cdot 7 \cdot 0.79, 1 \cdot 7 \cdot 0.79\} = \{7, 5.5, 5.5\}$$

$$SRL = \text{mean}[SRL_i] = 6$$

### Analysis

$SRL = 6$ , but the TRLs are all at 7. This alerts management that there is at least one interface or manufacturing issue. Examining the component SRLs reveals that  $SRL_1 = TRL_1 = 7$ , but the other two SRLs lag TRL, indicating that the interfaces from component 2 to 3 are lagging and should be addressed before developing the component technologies further.

### Practical Example—High Energy Laser System

Note: This is an example and not representative of any particular system. A high energy laser system is in early research and development, primarily funded by 6.2 and 6.3 sources. It is composed of at least the following subsystems: laser, beam director (BD), thermal management (TM), electrical management (EM), structural support (Struct), atmospheric propagation (Atmos), target, target acquisition, tracking, pointing (ATP), and battle management and controls (BM). A TRL assessment might be as follows (Table 4).

TABLE 4. SAMPLE TRL/MRL RATINGS

Subsystem	Laser	BD	TM	EM	Struct	Atmos	Target	ATP	BM	Controls
TRL	4	4	3	3	2	4	n/a	3	2	3
MRL	4	4	4	4	2	3	n/a	2	2	2

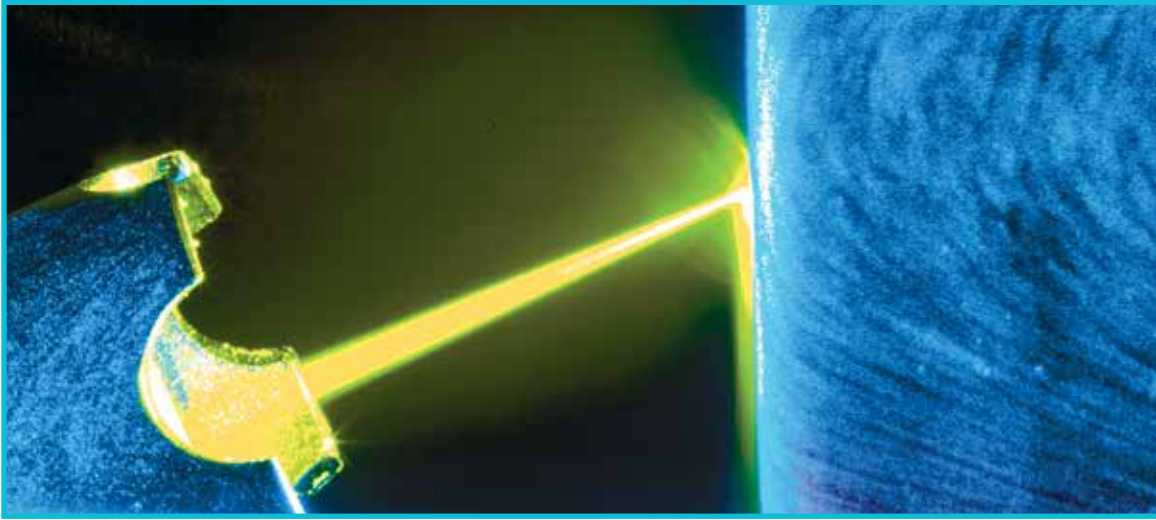
Note that the target TRL and MRL are “n/a” because the system does not involve building the target, but the atmosphere and ATP form an interface with the target so an IRL is associated with the target, but no TRL.

An IRL matrix might look as shown in Table 5, if most effort had been placed into developing the laser, beam director, ATP algorithms; and target information, but not much effort placed on ‘system’ issues, such as the electrical or thermal management systems or the controls architectures. For simplicity, only the upper half of the matrix is shown assuming that  $IRL_{ij} = IRL_{ji}$ .

TABLE 5. SAMPLE IRL RATINGS										
IRL	Laser	BD	TM	EM	Struct	Atmos	Target	ATP	BM	Controls
Laser	X	2	1	1	2	n/a	3	3	1	3
BD		X	2	3	4	2.5	2	2.5	1	3
TM			X	4	4	n/a	n/a	4	4	4
EM				X	4	n/a	n/a	4	4	4
Struct					X	2	n/a	3	4	4
Atmos						X	2	2	n/a	n/a
Target							X	2	n/a	n/a
ATP								X	2	2
BM									X	2
Controls										X

Not every component has every kind of interface so that the n/a values in Table 5 are simply not part of the calculation. Applying the equations in Tables 1, 2, and 3 yields the results shown in Table 6, assuming normalization by the 6.3 funding values from Table 1 and Table 2. The  $SRL = 2.19$ . The average  $TRL = 3.1$ .

TABLE 6. SAMPLE IRL, MRL AND SRL COMPONENTS										
Subsystem	Laser	BD	TM	EM	Struct	Atmos	Target	ATP	BM	Controls
$\bar{irl}_i$	0.67	0.81	1.1	1.14	1.13	0.71	0.75	0.91	0.86	1.05
$mrl_i$	1	1	1	1	0.5	0.75		0.5	0.5	0.5
$SRL_i$	2.67	3.26	3.29	3.43	1.13	2.13		1.36	0.86	1.57



The average SRL is below the average TRL, indicating that there are some integration or manufacturing issues that should be addressed before the components are developed further. Specifically, the laser subcomponent itself is a TRL 4, with an appropriate level of manufacturability; however, its average IRL is the lowest of any of the other subsystems. Such a system is in danger of developing a main component that cannot be integrated, demonstrated with a prototype system at an appropriate level, or that will come up with extensive integration issues late in development. These integration issues may prove to be very costly and time-consuming to fix. It would be best to develop the laser-thermal, laser-electrical, laser-battle management, and laser control interfaces before continuing to mature the laser technology itself. The side benefit would be the ability to demonstrate early prototype laser systems rather than waiting for full maturity of the final laser to conduct any demonstrations, which would be conducive to maintaining the interest in funding this technology development effort.

## Verbal System Readiness Level Definitions

The proposed mathematical definition of SRL permits a verbal definition of SRLs in a way that the Sauser definition and mathematics did not. There is one caveat to these verbal definitions: they strictly hold fast at those milestones of development where  $SRL = TRL$ . It is possible to have an SRL of 3 with TRLs of 6 by ignoring interfaces and manufacturing, in which case

the following definition of SRL = 3 (Table 7) would not be accurate because the SRL metric is significantly lagging the TRL metrics. This caveat also helps ensure that one cannot inappropriately claim a high level of SRL by having one mature component mask a less mature one.

TABLE 7. SYSTEM READINESS LEVEL DEFINITIONS		
SRL	Name	Definition
1	System concept	The system concept has been identified to include the subsystems. Overall system functional requirements are qualitatively understood.
2	System technologies	Subsystem technology path identified to include a specific technology solution. Technology, manufacturing, and interface drivers understood.
3	System proof of concept	Experimental evidence has been obtained that the system is possible in principle to develop and manufacture.
4	System component verification	All system components have been built and tested in a laboratory environment separately. Numerical studies show component compatibility.
5	System component validation	All system components have been built and tested in a relevant or emulated production and deployment environment. Components with simulated interfaces have been tested.
6	System prototype demonstration	A system prototype has been demonstrated and fabricated in a relevant environment. Interface control has been demonstrated traceable to a deployed environment.
7	System operational demonstration	An integrated system prototype has been demonstrated and fabricated in an operational / manufacturing environment.
8	Actual system demonstration	The production representative system has been demonstrated in an operational environment.
9	Operational system	Production system is used, demonstrated, and maintained in an operational environment.

Generalized Integration Readiness Level Definitions

The author proposes the simplified critical item lists (Table 8) for the IRLs (U.S. Navy, 2009). The simplified lists allow a wider application to physical rather than IT systems, and focus on the few truly critical milestones rather than many contributing factors. See U.S. Navy (2009, p. 6) for a comparison.

TABLE 8. SIMPLIFIED INTEGRATION READINESS LEVEL DEFINITIONS

IRL	Name	(Sauser et al., 2010) Definition	Critical Items
1	Identification	An <i>Interface</i> between technologies has been identified with sufficient detail to allow characterization of the relationship.	<ul style="list-style-type: none"> <li>• There exists a functional flow block diagram for the technology and its interfaces in a notional system concept.</li> <li>• Subject matter experts for each of the connecting technologies have been identified and a technical interchange held.</li> </ul>
2	Characterization	There is some level of specificity to characterize the <i>Interaction</i> (i.e., ability to influence) between technologies through their interface.	<ul style="list-style-type: none"> <li>• Input and output parameters have been identified for each interface.</li> </ul>
3	Compatibility	There is <i>Compatibility</i> (i.e., common language) between technologies to orderly and efficiently integrate and interact.	<ul style="list-style-type: none"> <li>• Parametric or physics-based models describe the interface at the qualitative level so that the impact on each of the identified parameters can be modeled at the system level.</li> <li>• Interface risks have been identified.</li> <li>• Interface constraints have been identified.</li> </ul>
4	Quality and Assurance	There is sufficient detail in the <i>Quality and Assurance</i> of the integration between technologies.	<ul style="list-style-type: none"> <li>• A solution space exists to meet design concept requirements.</li> <li>• Generic interface models have been validated by experiment.</li> </ul>
5	Control	There is sufficient <i>Control</i> between technologies necessary to establish, manage, and terminate the integration.	<ul style="list-style-type: none"> <li>• Interfaces are well defined.</li> <li>• Interfaces have been demonstrated in a laboratory environment.</li> <li>• Specific interface models have been validated by experiment.</li> </ul>

TABLE 8, CONTINUED			
IRL	Name	(Sauser et al., 2010) Definition	Critical Items
6	Information	The integrating technologies can <i>Accept, Translate, and Structure Information</i> for their intended application.	<ul style="list-style-type: none"><li>Control architecture is developed.</li><li>Software components work together.</li><li>Individual modules are tested with control signals to verify performance.</li><li>Integrated system demonstrations are completed.</li></ul>
7	Verification and Validation	The integration of technologies has been <i>Verified and Validated</i> with sufficient detail to be actionable.	<ul style="list-style-type: none"><li>Fully integrated prototype in simulated operational environment.</li><li>Each interface tested under stressed and anomalous conditions.</li></ul>
8	Mission Qualified	Actual integration completed and <i>Mission Qualified</i> through test and demonstration, in the system environment.	<ul style="list-style-type: none"><li>System is fully integrated in an operational environment.</li><li>All flight and safety qualifications are completed for all technologies and interfaces.</li><li>Form, fit, and function are verified.</li></ul>
9	Mission Proven	Integration is <i>Mission Proven</i> through successful mission operations.	<ul style="list-style-type: none"><li>System is fully integrated and has demonstrated operational effectiveness.</li><li>Interface failure rates are fully characterized.</li></ul>

Use of the SRL Metric

Any time the performance or behavior of a complex system is summarized by a single number, there is inevitable loss of information and the potential for false indication. SRL and IRL have a subjective component to them, as do TRL and MRL. The existence of the SRL metric will not completely compensate for organizational or programmatic pressure to advance technologies prematurely to meet budget and schedule. It will, however, foster an awareness of the cost of doing so. The SRL metric, as defined herein, is designed to be an indication that a system or component is ready for the next step in development when the system readiness is commensurate with the technology readiness. From equations (5) and (11), where  $SRL = \overline{TRL}$  at the system level and  $SRL_i = TRL_i$  at the component level, advancement is appropriate. Since interfaces cannot be more mature than their component

technologies, SRL will lag TRL at each step of development. At that point, the program will move to a higher funding, maturity, or development category; the normalization factors will change; and SRL will once again lag TRL as shown conceptually in Figure 7. This built-in safeguard will reduce the possibility of a mature subset of the system overshadowing a less mature part and giving false indications (Kujawski, 2010). A further safeguard can be implemented by limiting the values of the normalized IRLs and MRLs (*mrl* and *irl* from Tables 1 and 2) to a maximum of 1.0, further ensuring that one mature component cannot mask a less mature one. The principle that advancement to the next level of funding or acquisition should not occur until the system readiness is commensurate with the technology readiness can and should be applied at the system level (when  $SRL = \text{mean}[TRL_i]$ ) and at the component technology level (when  $SRL_i = TRL_i$ ).



## Conclusions

This article has proposed a modification to the Sauser mathematics of IRL and SRL that allows an SRL metric that gives a clear indicator of when a component technology or system is ready for further advancement and allows for standard verbal definitions of SRL. SRL and IRL need to be incorporated into the system engineering process early in development. TRL has been a valuable metric; however, its lack of emphasis on systems issues has resulted in divergent development, where some system components are developed beyond their interfaces and manufacturing, resulting in legacy decisions that impede demonstration and integration. A useful SRL metric can help to foster more balanced and cost-effective technology development.



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# Appendix

## Standard Technology Readiness Level and Manufacturing Readiness Level Definitions

TABLE A-1. STANDARD TRL DEFINITIONS	
TRL	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Component and/or breadboard validation in a laboratory environment
5	Component and/or breadboard validation in a relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in an operational environment
8	Actual system completed and qualified through test and demonstration
9	Actual system proven through successful mission operations
Note. (DoD, 2011)	

TABLE A-2. STANDARD MRL DEFINITIONS	
MRL	Definition
1	Basic manufacturing implications identified
2	Manufacturing concepts identified
3	Manufacturing proof of concept developed
4	Capability to produce the technology in a laboratory environment
5	Capability to produce prototype components in a production-relevant environment
6	Capability to produce a prototype system or subsystem in a production-relevant environment
7	Capability to produce systems, subsystems, or components in a production-representative environment
8	Pilot line capability demonstrated; ready to begin Low Rate Initial Production
9	Low Rate Initial Production demonstrated; capability in place to begin Full Rate Production
10	Full Rate Production demonstrated and Lean production practices in place

*Note.* (DoD, 2012)

TABLE A-3. DoD STANDARD FUNDING CATEGORIES	
6.1	Basic Research
6.2	Applied Research
6.3	Advanced Technology Development
6.4	Advanced Component Development and Prototypes
6.5	System Development and Demonstration
6.6	RDT&E Management Support
6.7	Operational Systems Development

*Note.* (DAU, 2016)

## Biography



**Dr. Sean Ross** has worked at the Air Force Research Laboratory, Directed Energy Directorate, since 1994. He is currently on a career-broadening assignment in the office of the Deputy Assistant Secretary of the Air Force for Science, Technology and Engineering. He is the author of “Laser Beam Quality Metrics” textbook and frequently teaches courses on the subject. Dr. Ross led the creation of the Environmental Laser Test Facility to test high-energy laser systems and components in simulated flight environments prior to flight testing. He has been involved in power, thermal, structural and other high-energy laser integration issues for over a decade. Dr. Ross holds a BS and MS in Physics from Brigham Young University and a PhD in Optical Science and Engineering from the Center for Research and Education in Optics and Lasers, College of Optics and Photonics.

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Systems engineers are faced with the difficult challenge of adhering to broad systems engineering (SE) policies, while simultaneously tailoring SE processes to meet the unique challenges facing their projects. Tailoring is often performed in an ad hoc manner. Determining which stages, steps, and artifacts of the process are necessary can be time-consuming and challenging. SE guidebooks across industry and government organizations often stress the importance of tailoring, yet offer little practical guidance on how to perform the function. This article proposes a model for automating the SE tailoring process through the definition of an organizational rule set and a minimal set of project-specific inputs. The model is then analyzed through several case studies within the Department of Homeland Security to evaluate the proposed approach.

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**Keywords:** *systems engineering, process tailoring, systems acquisition, method engineering, tailoring considerations*



Most organizations develop their own systems engineering (SE) guidelines to specify the stages, reviews, and artifacts that should be executed on projects. Standard processes are important for today's projects, as they employ standardized terminology and may prevent project teams from reinventing the wheel; however, formal and informal processes must be balanced to yield the efficiencies gained through standardization and the effectiveness gained by adaptability (Laufer, 2001, p. 27). Since no two projects are identical, no two processes are either (Humphrey, 1989, p. 241). Organizations must develop tailorable guidelines that are broad enough to span the range of projects within their portfolio (Hwang & Park, 2006, p. 37). This places the burden of tailoring the organization's SE guideline on project systems engineers. This article proposes a rule-based approach to partially automating this activity, thereby reducing the manual burden yet still offering a significant number of custom SE process variations to best meet a project's needs.

## Process Tailoring

Process tailoring refers to the modification of a standardized process to meet the unique needs of a project (Xu & Ramesh, 2007, p. 293). This can include determining which stages and reviews are necessary and should be executed multiple times, which artifacts should be produced, or even what content within an artifact is necessary. Successful tailoring results in modified processes that achieve the goals of the standard process model (International Organization for Standardization/International Electrotechnical Commission/Institute of Electrical and Electronics Engineers [ISO/IEC/IEEE] 15288, 2015, p. 86). Project teams often perform tailoring in an ad hoc manner without guidelines or rules (Pedreira, Piattini, Luaces, & Brisaboa, 2007, p. 1), and usually complete the activity based on declarative memory (Xu & Ramesh, 2009, p. 282). Process implementation directly affects project budget and schedule, as well as product quality. Choosing and adapting





the right design method is critical to successfully executing SE concepts and principles (Verma & Fabrycky, 1997, p. 592). Systems engineers are thus faced with the difficult challenges of adhering to broad policies.

While research related to process tailoring in software engineering is prevalent, similar research in SE is limited. Existing SE guidelines and handbooks stress the importance of tailoring SE processes to meet the unique needs of a project, but provide little guidance on process tailoring (Browning, Fricke, & Negele, 2006, p. 119; Pereira et al., 2007, p. 72). Fortune and Valerdi (2013) propose a framework for reusing SE products within an organization, and highlight key considerations for process reuse. Among them, Fortune and Valerdi (2013, p. 310) argue that a robust knowledge management system is critical to the success of process reuse. They also note the reuse of a product at too high a level may not apply to the specific environment of the new project. On the other hand, reusing products at too low a level can cause tailoring of enough significance that the effort saved by process reuse may be lost (Fortune & Valerdi, 2013, p. 305).

Process tailoring can be considered as a form of standard process reuse (Yoon, Min, & Bae, 2001, p. 202); however, tailoring involves process application to a unique project environment, as opposed to the flexibility of the standard process itself. Particularly in the field of software engineering, patterns have been explored as a viable option for process reuse; in fact, Cloutier and Verma (2007) extend the concept to a method for developing pattern forms in systems architecture. In addition, Hagge and Lappe (2005, p. 24) emphasize the need for capturing knowledge that can be reused in future projects. They propose four introductory patterns for requirements engineering and discuss a method for sharing observations across projects (Hagge & Lappe, 2005).

## Method Engineering

Extending knowledge from the software process domain to the SE process domain has been ongoing for quite some time (Boehm, 2006, p. 5). Research in software process tailoring is well-documented and can be extended to SE. Henderson-Sellers, Ralyté, Ågerfalk, and Rossi (2014) provide an extensive literature review of the application of Method Engineering (ME) to specific situations in software development. Their review spans the various approaches to method tailoring and case studies in the application of method tailoring. Kuhrmann, Méndez Fernández, and Tiessler (2014) also conducted a thorough literature review of ME, which pertains to the process

of constructing methods for software development. They highlight 83 articles contributing to the research of software process tailoring, and conclude that “strong empirical evidence of the feasibility of ME” is still lacking.

### **Software Process Tailoring Approaches**

A wide variety of approaches to software process tailoring have been documented in literature. The case retrieval-based method formulates a tailored software process based on retrieving a tailored process from a library of historical projects (Ahn, Ahn, & Park, 2003; Park & Bae, 2013). Retrieval is performed by comparing values of domain factors of a new project to those of past projects in the library. Two primary challenges exist with the case retrieval approach. First, the extensiveness of the library of previous methods, which requires a mature organization, limits the accuracy of the case retrieval approach. And second, the organization must have an established knowledge management system that not only archives previous projects, but also tags the projects with the values and domain factors required for retrieval.

In the preformed approach, an organization develops a standard set of tailored processes that apply to particular categories of projects (Plogert, 1996). The challenge with this approach is that it only includes the first level of tailoring, such as hardware or software, and does not address the significant variability that can exist from project to project within an organization. In addition, this approach does not easily allow for growth; to modify the approach based on lessons learned would require revisiting the pretailored processes altogether.

Hausen (1998) employs a rule-based approach to software process tailoring. The rule-based approach identifies values of factors that address the rationale for tailoring based on specific project characteristics. An engineer creates each rule such that for a specific value of a domain factor that exists for a new project, certain process elements are tailored (Kang, Song, Park, Bae, Kim, & Lee, 2008, p. 54). Kang et al. (2008) goes further by combining the rule-based approach with case retrieval where rules are used to retrieve the case most similar to the attributes of the new project.

Jaufman and Münch (2005, pp. 328–342) used both top-down and bottom-up approaches to software process tailoring, allowing for increased efficiency and process adherence, respectively. This approach leverages both the preformed and rule-based methodologies.

Hanssen, Westerheim, and Bjørnson (2005) use brainstorming to tailor a software process in an organization. Baldassarre, Caivano, Visaggio, and Visaggio (2002) propose the use of patterns for software process tailoring.



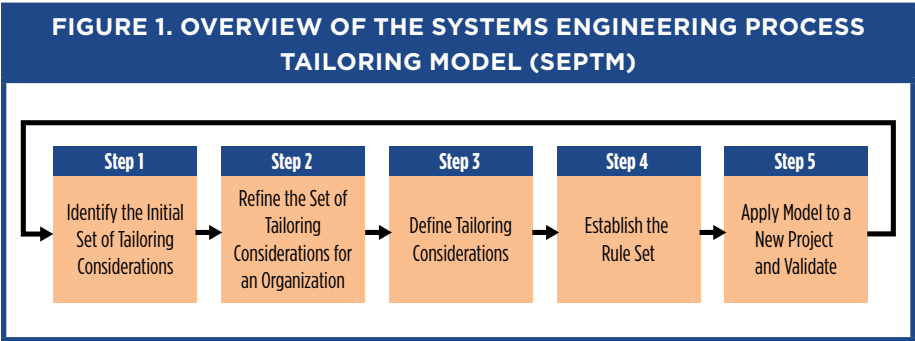
As previously stated, a significant amount of research exists in process tailoring for the software engineering field. While similar research exists in SE process tailoring, the opportunity exists to apply software engineering research to SE.

By proposing a model that simplifies SE process tailoring, this article seeks to bridge the gap in SE literature between SE process research that stresses the importance of tailoring yet offers little guidance on how to perform the function, and the practitioners who have to perform SE process tailoring to meet the specific needs of their projects. The proposed rule-based approach to SE process tailoring offers a significant number of custom SE process variations as compared to the preformed approach and without the reliance on a deep repository required of a case-retrieval approach. With this proposed approach, the number of tailoring decisions could be reduced from the total number of elements in a governing SE process to the number of rules established within an SE organization and applied to the project.

The next section of this article proposes the SE Process Tailoring Model (SEPTM), developed starting with tailoring considerations identified in the *INCOSE Systems Engineering Handbook*, published by the International Council on Systems Engineering (INCOSE, 2015), and that can be used to generate a project-specific SE process based on a project's unique characteristics and environment. The discussion on the SEPTM is then followed by a section that introduces the analysis of 24 case studies within the Department of Homeland Security (DHS), thereby evaluating the model against real world SE process tailoring instances. Finally, the article highlights conclusions of the research and areas of future work.

# Systems Engineering Process Tailoring Model (SEPTM)

Figure 1 presents an overview of the proposed SEPTM. At a high level, the authors constructed the model based on an analysis of the generic SE process described in the *INCOSE Systems Engineering Handbook* that influences process tailoring. This analysis forms the basis of an initial set of Tailoring Considerations (TC). From the initial set of TCs, a subset is then selected that is applicable to a particular organization. A rule set is developed that links the TCs and the organizational SE process. A systems engineer can then apply the rule set to the unique attributes of a project to generate a customized SE process based on the conditions of a particular project. The following subsections further describe each of these activities.



## Identify the Initial Set of Tailoring Considerations

An important aspect of the model is determining the TCs used to identify critical aspects of a project. The TCs will broadly inform what SE activities are needed for a given project. The development of the initial organizational TC list is based on an analysis of the general SE process described in the *INCOSE Systems Engineering Handbook* and its discussion of considerations and enablers for process tailoring (INCOSE, 2015). The handbook states the appropriate approach will vary based on the unique needs of a project. It also describes various life-cycle approaches, including the waterfall, incremental, and agile approaches. In the waterfall approach, the project team performs SE stages serially; in the incremental approach, the project team performs SE stages serially multiple times; and in the agile approach, the project team iterates through short development cycles with frequent product releases (Aoyama, 1998). As part of the agile development cycles, project teams perform the SE stages of requirements definition, design, development, and testing in an iterative fashion. Moreover, project teams perform and update the associated reviews and documentation with

each release (Cao & Ramesh, 2008, p. 63). Each of these approaches varies in terms of stage and review frequency, as well as the amount of documentation required. As a result, a project's life-cycle approach must be a critical TC.

The *INCOSE Systems Engineering Handbook* also describes cross-cutting technical methods and includes a section on specialty engineering analyses that must be considered by a project's systems engineer; however, not all of the analyses will apply to every project (INCOSE, 2015). For example, interoperability should be considered for projects that interface with other projects. An organization may have specific artifacts that are required to address interoperability for certain projects or allow for deleting interoperability artifacts based on the project type.

The handbook's tailoring section includes a discussion of SE process tailoring and identifies considerations and enablers for tailoring: project scope, risk tolerance, complexity and precedence of the system, and organizational/enterprise policies and infrastructure (INCOSE, 2015). While the handbook identifies risk tolerance as a factor in process tailoring, it does advise of the importance of placing tailoring emphasis on the system and the project objectives, or project scope.

Analysis of the general SE process and tailoring discussion in the *INCOSE Systems Engineering Handbook* resulted in the following list of TCs:

TAILORING CONSIDERATIONS	
Life-cycle Approach	Logistics Engineering Analysis
Project Scope	Manufacturing and Producibility Analysis
Complexity and Precedence of the System	Mass Properties Engineering Analysis
Organizational/Enterprise Policies and Infrastructure	Reliability, Availability, and Maintainability
Modeling, Simulation, and Prototyping	Resilience Engineering
Affordability/Cost Effectiveness/Life-Cycle Cost Analysis	System Safety Analysis
Electromagnetic Compatibility Analysis	Systems Security Engineering
Environmental Engineering/Impact Analysis	Training Needs Analysis
Interoperability Analysis	Usability Analysis/Human Systems Integration
	Value Engineering

Of the 19 TCs, the first four—Life-cycle Approach, Project Scope, Complexity and Precedence of the System, and Organizational/Enterprise Policies and Infrastructure—apply to all organizations, as the *INCOSE Systems Engineering Handbook* suggests. The remaining 15 vary in applicability, depending on the types of projects an organization executes. This requires an organization to determine the appropriate subset of TCs for their project portfolio.

### **Refine the Set of Tailoring Considerations for an Organization**

In the second analytical step, the overarching TC list is reduced to one that includes only the TCs relevant for that organization. This step is performed by comparing the TC list to organizational policies and the organizational SE process. For each TC, possible values are identified. The TCs can have values that are either yes/no (e.g., environmental impacts need to be considered or not) or multiple (e.g., life-cycle approach may be waterfall, incremental, or agile). The case study in the next section of this article offers a more detailed discussion of how this step is performed.

### **Define Tailoring Conditions**

Before a tailoring rule set can be developed, some tailoring operations must be defined. For the purposes of this research, the following definitions apply:

- “Standard” is used when a stage, review, or artifact is to be developed consistent with the scope of the activity defined in the organizational SE policy.
- “Tailored” is used when a stage, review, or artifact is modified from the scope in the organizational SE policy. This could include combining two or more stages, reviews, or artifacts into one. This could also include repeating stages or reviews multiple times within a project. For example, the process tailoring model recommends that the Critical Design Review occur multiple times in a project that uses incremental development methodology.
- “Deleted” is used when the stage, review, or artifact is not needed and removed from the project’s tailored SE process altogether. An example of this is the removal of a System Design Document for a Commercial Off-The-Shelf (COTS) acquisition.

Establishing the Rule Set

Once the TCs have been selected for an organization and tailoring conditions defined, a rule set must be generated to link the TCs and associated values to the elements of the organization’s standard SE process. Process elements are those SE tasks and activities identified within the organization’s SE process. Table 1 shows the matrix used to establish the rule set. In area 1 of the table, all of the elements (1 to M) of the standard SE process are listed vertically. For example, the DHS SE process has 107 process elements (“M”). In area 2, each TC (1 to N) and associated values (1 to O) are listed horizontally. “N” represents the number of TCs identified for the organization, and the values represent potential attributes of a project within the organization. As an example, if TC 1 is Interoperability Analysis, the potential values would be “yes” and “no” given that a system may be stand-alone or connected. For each intersection of a process element and a TC-value combination in area 3, a tailoring rule is established. This requires two levels of decisions. First, a determination is made as to whether a TC is relevant or not for a particular process element; and second, if so, a determination is made for each value of the TC whether the process element should be kept standard, tailored, or deleted. Thus, each relevant intersection in area 3 will contain either “S” for standard, “T” for tailored, or “D” for deleted. In summary, the resulting rule set is a list of TCs, for which each value drives a tailoring decision (standard, tailored, or deleted) for every relevant process element within the organizational SE process.

TABLE 1. ESTABLISHING THE RULE SET														
Tailoring Considerations →		TC 1				TC 2				...	TC N			
2	Values →	Value 1	Value 2	⋮	Value O	Value 1	Value 2	⋮	Value O	⋮	Value 1	Value 2	⋮	Value O
Standard SE Process Elements														
1	Process Element #1													
	...							3						
	Process Element #M													



## Apply Model to a New Project and Validate

Once the model has been developed for an organization, project systems engineers can use it for tailoring SE processes to meet the needs of a specific project. To do so, a systems engineer must have a solid understanding of the acquisition strategy and the project environment. This is true whether applying a rule-based methodology as is the case here, or tailoring an SE process in an ad hoc fashion. To exercise the model, a systems engineer must align characteristics of the project to a value associated with each TC. Once this is complete, the model outputs the tailored SE process, identifying which of the full set of the organization's SE process elements should be executed as standard, which should be tailored, and which can be deleted. After the model has been applied to a real-world situation, the organization must incorporate lessons learned back into the model by reassessing the organization's list of TCs and the organization's rule set. Moreover, as SE research is constantly refining best practices and industry standards are updated, the organization must also revisit the initial TC set to assess changes from industry.

## Case Study

The objective of this research is to use project attributes and a rule-based approach to reduce the amount of manual tailoring of the SE life cycle. Henderson-Sellers et al. (2014, p. 169) note that determining the best project methodology requires specific tailoring to a project's unique situation. Measuring the benefit of such an activity can be based on the amount of effort required to tailor standard processes (Xu & Ramesh, 2007). For purposes of this analysis, this article extends that definition to the number of manual decisions required to produce a project-specific SE process. By design, this model fixes the number of decisions on the number of TCs established for an organization. If an organization applies all of the initial 19 TCs, the number of manual decisions will be 19. The DHS, an organization with a large acquisition portfolio, has an SE process consisting of 107 process elements, resulting in 107 associated process tailoring decisions (DHS, 2010). Provided the model can reproduce the tailoring decisions made within the DHS case studies, the potential benefit of this proposed approach to SE process tailoring can be demonstrated by reducing manual decisions from 107 to 10, which as described in the following subsections, is the number of TCs determined for the DHS case study. As such, the following subsections focus on the accuracy of the model in comparison to case studies.

***The objective of this research is to use project attributes and a rule-based approach to reduce the amount of manual tailoring of the SE life cycle.***

**Case Study Data**

To perform the case study analysis, the authors required two key elements. First, an organization’s SE policy was required to serve as the process baseline. The baseline was used to establish the linkages between the overarching TCs and the process elements contained within the baseline. The data source for this research was the *DHS Systems Engineering Lifecycle Process Guide* (DHS, 2010). The DHS SE process identifies nine SE stages, 11 technical reviews, and 87 artifacts to be executed through the life of a project, for a total of 107 SE process elements.

The second key element required is a set of tailored SE processes implemented on projects within the organization. The authors selected 24 DHS projects for analysis based on data availability and variability across the TCs (Table 2). For example, some projects executed full research and development, while others were COTS acquisitions; some executed a waterfall development approach, and others, incremental or agile. The authors gathered and analyzed quantitative data regarding tailoring outcomes from each of the 24 projects and compared actual and modeled tailoring outcomes.

**TABLE 2. CASE STUDY PROJECT VARIABILITY**

<b>Case Study Tailoring Considerations</b>	<b>Possible Values</b>	<b># Projects</b>
Security Impact	Impact/No Impact	17/7
Privacy Impact	Impact/No Impact	9/15
Intelligence Impact	Impact/No Impact	3/21
Interoperability Impact	Impact/No Impact	11/13
Accessibility Impact	Impact/No Impact	13/11
Technology Demonstration Planned	Planned/Not Planned	7/17
Environmental Impact	Impact/No Impact	7/17
Development Methodology	Waterfall/ Incremental/Agile	11/11/2
Development Type	Development/COTS	19/6
Project Size	< \$300M, ≥ \$300M	6/18

## **Selection of Organizational Tailoring Considerations**

The first step in applying the tailoring model to an organization is to determine the subset of the 19 overarching TCs that are applicable to the organization. As stated previously, the first four TCs apply to all organizations and were adapted for the DHS TC list. Analysis of the DHS organizational/enterprise policies yielded additional considerations pertaining to privacy and intelligence. Additional analysis of the DHS SE process was performed to determine which of the remaining 15 are applicable. Of the 15, five were applicable to all projects per the DHS SE process, five were not discussed in the DHS SE process guide, and five may apply depending on the needs of the specific project. The five TCs that may be applicable were included as organizational TCs in the model. As a result, the 10 organizational TCs identified and applied for this research are as follows:

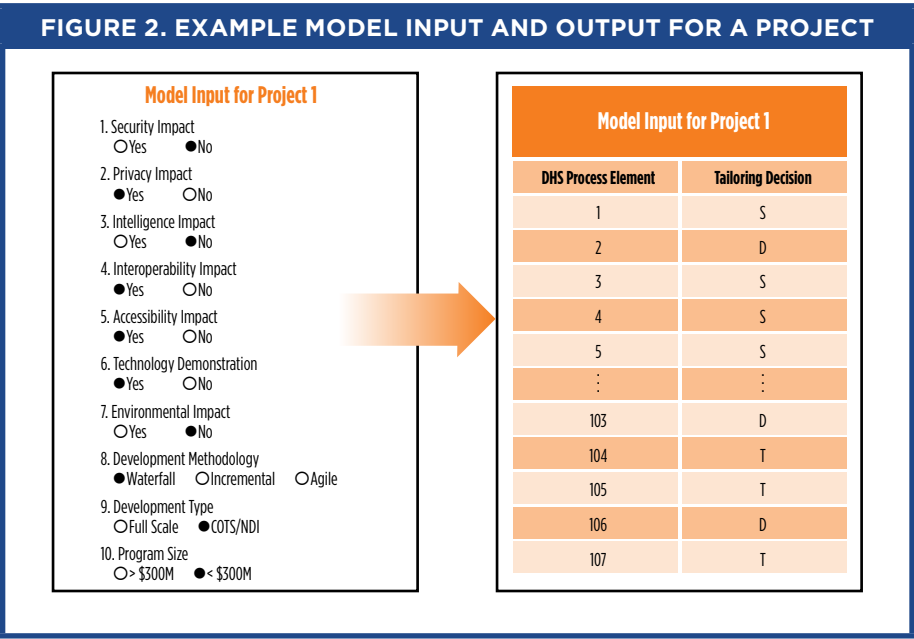
1. Security Impact
2. Privacy Impact (Organizational/Enterprise Policies and Infrastructure)
3. Intelligence Impact
4. Interoperability Impact
5. Accessibility Impact (Usability)
6. Technology Demonstration (Modeling, Simulation, and Prototyping)
7. Environmental Impact
8. Development Methodology (Life-cycle Approach)
9. Development Type (Complexity and Precedence of the System)
10. Project Size (Project Scope)

With the 10 organizational TCs in place, the rule set for DHS was established by linking the TCs to the standard DHS SE process as depicted in Table 3. Note that for any given TC, only a subset of process elements is relevant; that is, empty table entries reflect that there is no relevance between that TC and the intersecting standard SE process element. For example, in Table 3, four TCs (2, 7, 9, and 10) are relevant to process element No. 1.

TABLE 3. ESTABLISHING THE RULE SET FOR THE DHS CASE STUDY											
Tailoring Considerations →	TC 1	TC 2	TC 3	TC 4	TC 5	TC 6	TC 7	TC 8	TC 9	TC 10	
	Security Impact	Privacy Impact	Intelligence Impact	Interoperability Impact	Accessibility Consideration	Technology Demonstration	Environmental Impact	Development Methodology	Development Type	Project Size	
	Y	N	Y	N	Y	N	Y	W	A	D	C
	N	Y	N	Y	N	N	N	I		≥ \$300M	< \$300M
	Values →	Y	N	Y	N	Y	N	W	A	D	C
DHS Standard SE Process Elements											
Process Element #1		S	D				S	D		S	T
:											
Process Element #107		S	D		S	D	S	D		S	T
Note. Values: Y=Yes, N=No, W=Waterfall, I=Incremental, A=Agile, D=Developmental, C=COTS Entries: S=Standard, T=Tailored, D=Deleted											

Case Study Projects

With the rule set established for DHS as described previously, the next step was to input the attributes of each of the 24 projects into the model to generate a custom SE process for each project. Figure 2 depicts an example project’s input and output, highlighting that the input is addressing the 10 TCs based on project characteristics, and the output is a tailoring decision for each of the 107 elements within the DHS SE process.



Note. COTS/NDI = Commercial Off-The-Shelf/Nondevelopmental Item.

Three questions formed the analysis of each TC. Table 4 lists those questions and provides a corresponding example using the Security TC. The authors assessed each of the 10 TCs by comparing the model output for each project to the data from each project’s SE process tailoring plan. A default process was established based on default project attributes within the rule set. Projects that had an attribute different from the default were compared to the model for that particular attribute. For example, the default project attribute for the Security TC is “No”; therefore, the 14 projects that do have security impacts were compared to the model to assess whether the projects performed the process elements relevant to that TC.

**TABLE 4. CASE STUDY ANALYSIS QUESTIONS**

<b>Analysis Question</b>	<b>Security TC Example</b>
For a given pairing of process element and tailoring consideration, does the tailoring decision generated by the model for a project match the tailoring decision actually executed on the project?	For a project with security impacts, did the model and project data both include a plan to execute the disaster recovery plan process element?
For the given pairing of process element and tailoring consideration, what percentage of matches between the project data and their corresponding model outputs exists?	For the 14 projects that do have security impacts, what percentage of the projects included a plan to execute the disaster recovery plan process element as the model suggests?
What percentage of process elements have at least 75% matching between model output and actual project data?	What percentage of the 15 process elements relevant to the Security TC have a 75% match between model output and actual project data?

Table 5 summarizes the case study analysis approach using the Security TC as an example. Questions listed in Table 4 trace to Table 5 as “Q1”, “Q2”, and “Q3”. Column 1 represents the process elements relevant to the Security TC. Column 2 shows the tailoring decision of the model for the Security TC and relevant process elements; the next set of columns shows the pertinent data from the 24 projects, and an assessment of whether or not each matches the model (Q1). The last column in the table calculates the percentage of projects that match the model for each process element (Q2). Consistent with validation studies of software engineering practices, a 75 percent acceptable matching level is used (Daneva & Ahituv, 2010, p. 282; Krishnan & Kellner, 1999, p. 806; Ramasubbu, Krishnan, & Kompalli, 2005, p. 83). Thus, for a TC to be considered valid, the model output for each relevant process element must match at least 75 percent of the relevant projects (last column in Table 5), and at least 75 percent of the process elements linked to that TC must meet that threshold (Q3). This process described for the Security TC was repeated for each of the 10 TCs.

TABLE 5. CASE STUDY ANALYSIS EXAMPLE							
Process Elements Relevant to Security TC	Model	Project 1		...	Project 24		Q2. % Match (Must be ≥ 75%)
		Data	Q1. Match to Model?		Data	Q1. Match to Model?	
36. FIPS 199 Security Categorization	S	S	Y	...	D	N	89
53. Security Requirements Traceability Matrix	S	D	N	...	D	N	74
54. Plan of Actions and Milestones	S	D	N	...	D	Y	85
55. System Security Plan	S	S	Y	...	S	Y	100
56. Disaster Recovery Plan	S	S	Y	...	D	N	89
57. Security Risk Assessment (SRA)	S	D	N	...	D	N	74
59. Security Test and Evaluation Plan	S	D	N	...	D	Y	85
61. Contingency Plan	S	S	Y	...	S	Y	100
64. Interconnection Security Agreement	S	D	N	...	D	N	74
84. Security Assessment Report	S	D	N	...	D	Y	85
85. Security Accreditation Package	S	S	Y	...	S	Y	100
92. Authority to Operate Letter	S	S	Y	...	S	Y	100
100. FISMA Metrics Report	S	S	Y	...	D	N	89
101. Security Incident Reports	S	D	N	...	D	N	74
102. C&A Updates	S	D	N	...	D	Y	85
Q3. % Meeting Threshold (must be > 75%)							95%

Note. C&A = Certification and Accreditation; FIPS = Federal Information Processing Standards; FISMA = Federal Information Security Management Act.

Case Study Results

Before presenting the specific results of the case study analysis, the following key points must be noted:



- As stated in the previous section, the analysis focused on the project attributes that are not the default. As such, the table of results highlights the nondefault attributes and the associated comparative results to the model.
- Additionally, the Life-cycle Approach TC consisted of three options: waterfall, incremental, and agile. These three were chosen based on the common development methodologies used in DHS. With waterfall applied as the default attribute for the standard process, the analysis focused on incremental and agile.
- In the analysis of the 11 projects using the incremental development methodology, we discovered the tailoring plan for each was limited to a single increment of the project, with a corresponding note that the tailoring plan would be updated prior to initiation of each new increment. As such, the incremental development projects actually reflected a waterfall-based tailoring strategy.
- For the development methodology, the table of results then focuses on the projects that use the agile method, and assesses whether the model matches the tailoring approach of those projects for the process elements that correspond to the Life-cycle Approach TC.

Table 6 shows the results of the analysis comparing the relevant projects to the model outputs. The number of projects with each particular attribute is provided. Overall, the results show that nine of the 10 TCs can be used to reduce the amount of manual tailoring for a particular project. The one exception is the “Project Size” TC. As discussed previously, there is limited specific research regarding the application of SE based on project size, and more specifically, to small projects. Laporte, Alexandre, and Renault (2008, p. 98) discuss the need for developing international standards to address the needs of small development organizations; one objective is to “provide harmonized documentation” integrating standards, work products, and deliverables. This naturally extends to SE within small organizations and large organizations with small projects in their portfolio. Our analysis showed that low correlation exists between the model and the small project case studies. This occurred because of the following: while very few projects tailored the process elements recommended by the model, each project

team executed, on average, 90 percent of the relevant process elements. As a result of their small size, few projects leveraged the opportunity to tailor process elements.

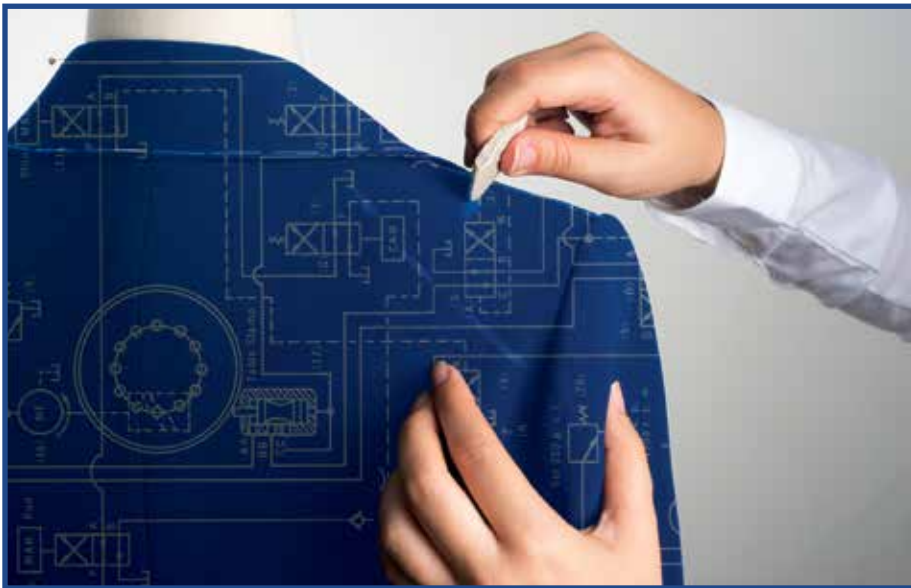
TABLE 6. CASE STUDY ANALYSIS RESULTS					
ID	Project Attribute	# Relevant Projects	# Process Elements	# Process Elements With ≥ 75% Match to the Model	% Process Elements With ≥ 75% Match to the Model
1	Security Impact	17	15	15	100%
2	Privacy Impact	9	4	4	100%
3	Intelligence Impact	3	1	1	100%
4	Interoperability Impact	11	8	6	75%
5	Accessibility Impact	13	2	2	100%
6	Technology Demonstration Planned	7	1	1	100%
7	Environmental Impact	7	1	1	100%
8	Agile Development	2	19	15	79%
9	COTS	6	9	7	78%
10	Small Project	6	20	2	10%

## Conclusions and Future Work

Process tailoring is critical to effectively and efficiently executing SE based on the unique characteristics of a project. Many SE processes recommend tailoring, but are not supported with tailoring guidelines. This article examines the previous research of process tailoring in software literature and SE standards for certain types of projects, and proposes a model for SE process tailoring. Our comparison of the SEPTM model to several case studies within the DHS shows rule-based process tailoring, coupled with project attributes, can be a viable approach to reducing the amount of manual tailoring required for a given project.

While our research objectives were accomplished for the development of the initial model, additional research should be performed in the area of SE process tailoring. Key elements requiring further research include:

- Very little research exists regarding SE process execution on small projects or in small project teams. The INCOSE Very Small and Micro Entities (VSME) Working Group is developing work packages that recommend various levels of SE process execution for small projects. The SEPTM described herein could be informed by the findings of their research.
- The model's "Complexity and Precedence of the System" TC is based on a selection of either development or COTS. The model should be further refined based on an investigation of COTS integration, which has become more common in recent years.
- The initial model is based primarily on the *INCOSE Systems Engineering Handbook*. Certainly any number of standard SE processes can be used as a starting point for organizational process tailoring; additional research should be performed to identify common tailoring considerations across a broader set of SE standards and literature.
- Investigate applications of data mining to the process of selecting the TCs that form the basis of the model.



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# Department of Defense Acquisition Program **TERMINATIONS:**

Analysis of 11 Program Management Factors

*Lt Col Patrick Clowney, USAF (Ret.), Jason Dever, and  
Steven Stuban*

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The research described herein aims to add to the body of knowledge of program management and factors that lead to acquisition program terminations within the U.S. Department of Defense (DoD). Specifically, this research surveyed three groups—DoD acquisition program managers, defense industry program managers, and defense industry consultants—to evaluate and analyze key program factors that influence DoD acquisition program terminations. This research used relative importance weight calculations and a chi-squared distribution analysis to compare the differences between DoD acquisition program managers, defense industry program managers, and defense industry consultants regarding the factors that lead to DoD acquisition program terminations. The results of this research indicate that a statistically significant difference does not exist between the three groups as to the relative importance of 11 program management factors.

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**Keywords:** *program management factors, relative importance weight calculations, DoD program termination*



The U.S. Department of Defense (DoD) loses billions of dollars annually on canceled or failed acquisition programs (DoD, 2013). In fact, many acquisition studies conducted by the Government Accountability Office (GAO), DoD, Office of Management and Budget, as well as many Federally Funded Research and Development Centers illuminate the myriad of programs that are terminated without meeting full operational capability (DoD, 2013).

From 1997 to the present, DoD spent in excess of \$62 billion on programs that were eventually canceled (Table 1 and Figure 1). The DoD has invested a great deal of time, energy, and resources to investigate the root causes of program cancellation and to determine why so many programs fail to make it through the acquisition system. In fact, The Office of Performance Assessments and Root Cause Analyses (PARCA), established in 2009 by the Weapon Systems Acquisition Reform Act of 2009, continuously evaluates the status of defense programs (Weapon Systems, 2009). PARCA issues policies, procedures, and guidance governing the conduct of such work by the Military Departments and Defense Agencies (Weapon Systems, 2009).

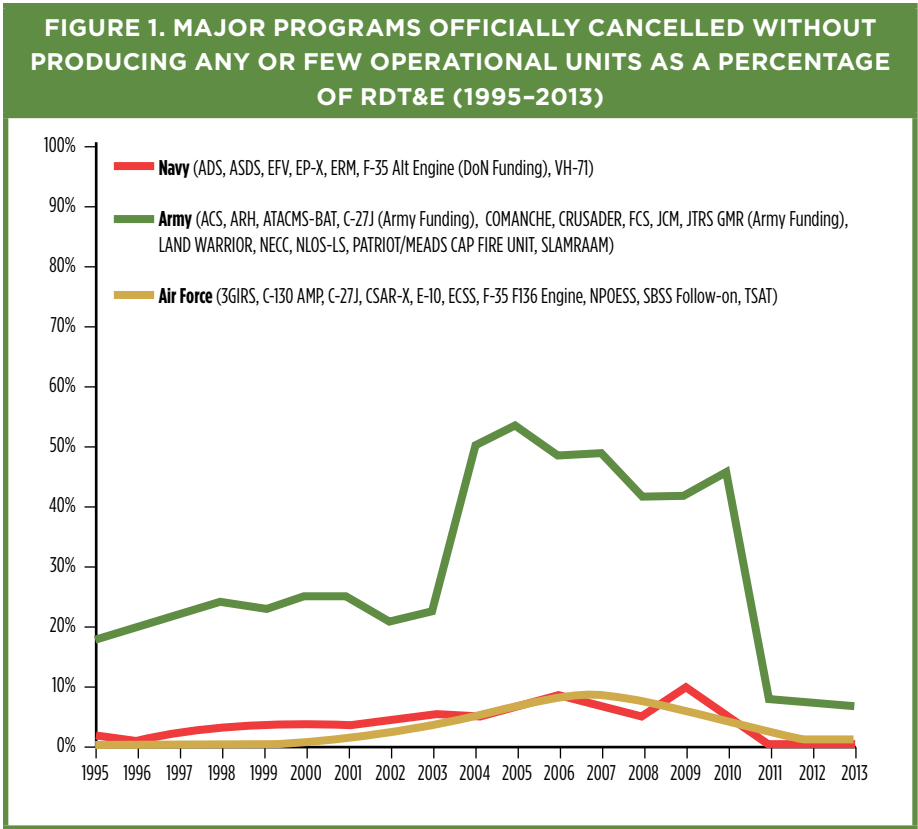




**TABLE 1. SELECTED DoD PROGRAM TERMINATIONS AND COSTS**

<b>Program</b>	<b>Service</b>	<b>Cost (\$billion)</b>	<b>Source</b>
Future Combat Systems	Army	20.00	GAO (2014)
Joint Tactical Radio System	Army	11.00	Rodriguez (2014)
Comanche Helicopter	Army	5.90	GAO (2014)
nPOESS Satellite	Air Force	5.80	Reed (2011)
Airborne Laser	Air Force	5.00	Rodriguez (2014)
VH-71 Presidential Helicopter	Marines	3.30	GAO (2014)
Expeditionary Fighting Vehicle (EFV)	Marines	3.30	Reed (2011)
Transformational SATCOM (TSAT)	Air Force	2.90	Reed (2011)
Crusader	Army	2.20	GAO (2014)
Kinetic Energy Interceptor	Missile Defense Agency	1.30	Rodriguez (2014)
Advanced SEAL Delivery System	Navy	0.60	Reed (2011)
Armed Reconnaissance Helicopter	Army	0.50	Reed (2011)
Aerial Common Sensor	Army	0.19	GAO (2014)
CG(X) Next Generation Cruiser	Navy	0.20	Reed (2011)
CSAR-X	Air Force	0.20	Reed (2011)
<b>TOTAL</b>		<b>62.39</b>	

*Note.* CSAR = Combat Search and Rescue; NPOESS = National Polar-orbiting Operational Environmental Satellite System; SATCOM = Satellite Communications; SEAL = Sea, Air, and Land.

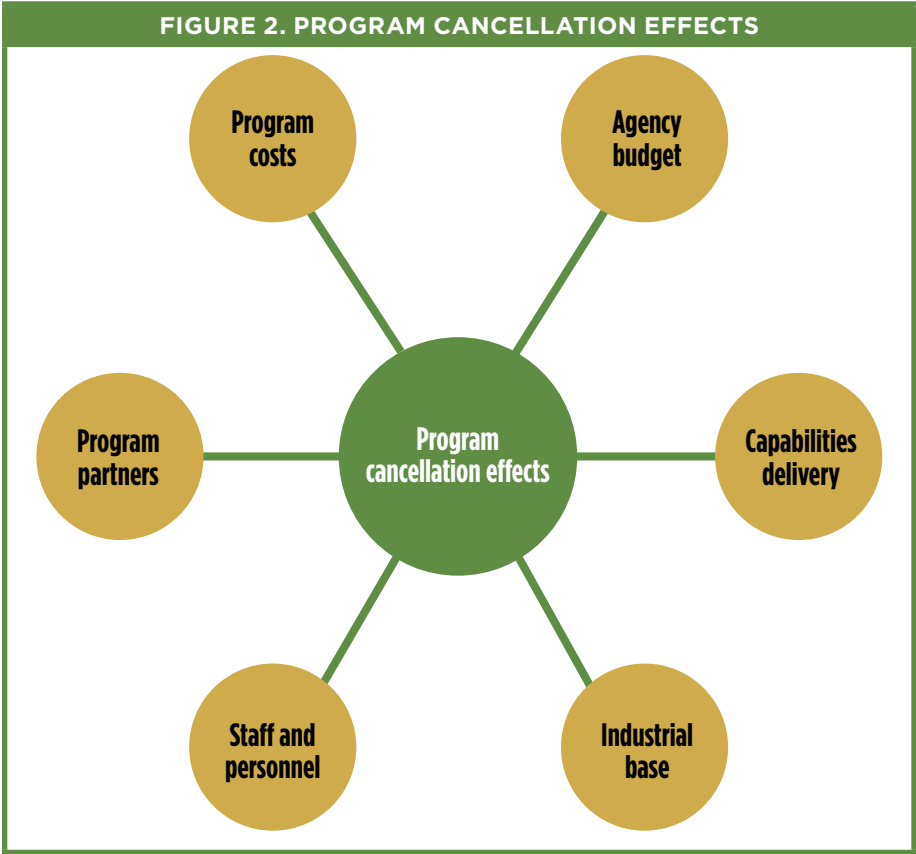


Note. (DoD, 2013)

ACS = Aerial Common Sensor; ADS = Advanced Deployable System; Alt = Alternate; AMP = Avionics Modernization Program; ARH = Armed Reconnaissance Helicopter; ASDS = Advanced SEAL Delivery System; ATACMS-BAT = Army Tactical Missile System Block II-Brilliant Anti-Armor; CSAR = Combat Search and Rescue; DoN = Department of the Navy; ECSS = Expeditionary Combat Support System; EFV = Expeditionary Fighting Vehicle; ERM = Extended Range Munition; FCS = Future Combat System; JCM = Joint Common Missile; JTRS GMR = Joint Tactical Radio System Ground Mobile Radio; MEADS = Medium Extended Air Defense System; NECC = Navy Expeditionary Combat Command; NLOS-LS = Non-Line of Sight Launch System; NPOESS = National Polar-orbiting Observing Satellite System; SBSS = Space Based Space Surveillance; SLAMRAAM = Surface-Launched Advanced Medium Range Air-to-Air Missile; 3GIRS = Third Generation Infrared Surveillance; TSAT = Transformational Satellite.

When programs are terminated, the DoD loses billions of investment dollars (Leanard, 2013). In some termination cases, the DoD garners value despite termination. Marginal benefits include economic value, knowledge, skills, lessons learned, and insights. Further, the effects of termination influence many areas of the acquisition enterprise.

Scholars, program managers, and systems engineers posit that a host of factors influences whether a program is terminated or allowed to continue. They include, but are not limited to, political pressures, cost overruns, schedule overruns, and performance shortfalls. Figure 2 illustrates the various effects of program termination (GAO, 2014).



*Note.* (GAO, 2014)

The purpose of this research was to compare the three groups that are primarily associated with DoD program and project management: DoD program managers, DoD program manager consultants, and DoD industry program managers. These three groups were selected for comparison because each works with DoD programs, but each group has a unique perspective. Exploring the different perspectives is essential for understanding acquisition systems (Cornell, 2009). Viewing and understanding systems from various perspectives increase the overall understanding and appreciation of acquisition program system dynamics (Cornell, 2009).

Most research into DoD program termination focuses on an analysis of scope, schedule, and budget. This research expands on those three primary factors and evaluates eight other factors. Although other factors were identified in the literature review that were not evaluated, the authors chose not to evaluate every factor in the literature. Instead, the authors chose to evaluate the 11 most common factors across the literature that explore program success, failure, and termination. This research aims to identify the factors that have the greatest influence on program and project cancellation from the expert's perspective, and capture any significant differences between DoD program managers, defense industry program managers, and defense industry consultants.

This research aims to answer two interrelated research questions to identify the factors that have the greatest influence on program and project cancellation from the expert's perspective. The research questions for this article include:

1. Are there any statistically significant differences between DoD acquisition program managers, defense industry program managers, and defense industry consultants as to the leading factors that result in DoD acquisition program terminations?
2. What are the critical factors and attributes that lead to DoD acquisition program terminations?

If statistically significant differences exist between the three groups as to the relative importance of cancellation factors, the research will identify where those differences exist. If statistically significant differences do not exist between the three groups as to the relative importance of cancellation factors, the research will identify the synergies between DoD program managers and defense industry program managers. In the first case, the differences could suggest future research to understand why different perspectives are prevalent. In the second case, the common responses could highlight/identify opportunities for emphasis to quell the frequency of program terminations.

Program and project failure and success are an enduring subject of investigation, discovery, and discussion in government, business, industry, and the private sector. Indeed, project termination usually comes with tremendous financial consequences and significant loss of time. Within the DoD, a great deal of research has





been conducted by Federally Funded Research and Development Centers (RAND, Center for Naval Analysis, MITRE, etc.), think tanks, and academia into some of the causes for program and project failure (Hofbauer, Sanders, Ellman, & Morrow, 2011). While most of this research focuses on the unique root causes for individual program failure, a comprehensive analysis at the aggregate level—using expert judgment to compare and contrast DoD program managers, DoD industry program managers, and DoD consultants—is missing in the literature. This research is the first step in a qualitative and quantitative analysis, using expert judgement at the aggregate level through a survey in order to assess the relative importance of recognized factors that lead to program and project termination.

## Literature Review

A key aspect of understanding program and project failure is an analysis of program and project attributes and factors that affect program and project management. The factors that influence program and project management success in multiple industries have been thoroughly investigated in academia. These factors serve as an outstanding analytical tool to provide a unique look into DoD acquisition program and project failures from a program and project management perspective. Essential to this task is identifying the key factors, understanding the root causes, and ascertaining the major influences of program and project failure to provide keen insight into DoD program and project failure. Because DoD program and project terminations cost American taxpayers billions of dollars, an investigation into this subject matter is imperative for DoD, defense industry, Congress, and systems engineering researchers in order to glean an enhanced understanding of DoD program and project failure, thereby ensuring efficient, effective, and successful program and project management.

An exhaustive literature review identified 11 critical factors associated with program and project management for examination. Program and project management, project failure, project success, and the factors that lead to project failure and project success remain important issues of significant interest to program managers, decision makers, and executives within the DoD. The literature is replete with scholarly articles and research into this endeavor. The articles pertaining to factors that impact project management, success, and failure generally fit into several broad categories. Such categories may include value of project

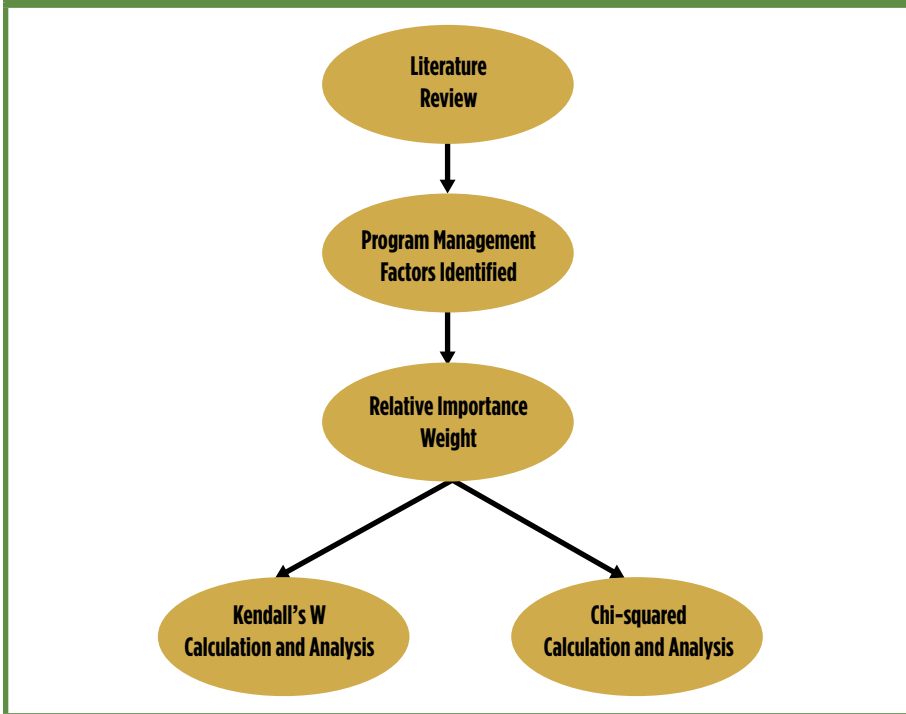


management; project success criteria; project failure criteria; project management rubrics; case studies; and industry-specific research, consulting services, and independent studies, such as information technology, construction, and engineering. Further, a significant body of research focuses on the roles of managers in project failure. The following discussion is a brief summary of the most salient research on program and project management, failure, and success within the literature. The 11 factors identified in the literature review served as the factors for analysis.

***A key aspect of understanding program and project failure is an analysis of program and project attributes and factors that affect program and project management.***

Pinto and Slevin (1987) developed a framework (Figure 3) for understanding the implementation of projects, as well as a diagnostic tool for the project manager known as the Project Implementation Profile (Pinto & Slevin, 1987). Their research focused on identifying predictive factors of successful program and project management, and serves as a seminal work for all discussions on program and project management; their research identified the following 10 factors (Pinto & Slevin, 1987):

1. Project mission
2. Top management support
3. Project schedule plan
4. Client consultation
5. Personnel and recruitment
6. Technical tasks
7. Client acceptance
8. Monitoring and feedback
9. Communication
10. Troubleshooting

**FIGURE 3. PROJECT IMPLEMENTATION PROFILE**

Note. (Pinto & Slevin, 1987)

Their framework showed that the factors are dynamic. Pinto and Slevin claim that when studying program and project management, the factors follow a logical progression. Despite recognizing the interdependence of the factors on each other, their study did not explore this finding.

Pinto and Slevin further suggest that their framework is an effective tool for project managers. Project managers can use their framework as a means to manage and monitor the project's posture as well as determining where the project is related to its life cycle. Their tool can also be used as a measure of project success. They developed a Likert scale instrument whereby a project manager can measure the importance of each factor on a given program or project at different points in the life cycle to determine which factor is most important.

Additional research conducted by Lawrence and Scanlan (2007) provides tremendous value into project failure in defense industries. They were involved in a 10-year research project of U.S. and European aerospace industries to create methodologies and tools for large aerospace project managers

(Lawrence & Scanlan, 2007). The study was commissioned to address a large amount of project terminations in U.S. and European aerospace industries. Although their focus was on aerospace industries, the authors maintain that their findings are universal to large engineering projects within all industries (Lawrence & Scanlan, 2007). Many interviews with program and project managers revealed that causes of project termination were not singularly the project managers' fault. Program and project managers were characterized as highly intelligent and extremely competent. They concluded that more robust software tools are needed to manage the complexities of today's multifaceted engineering projects. However, they also identified eight other critical elements that strongly impact project success or failure (Lawrence & Scanlan, 2007). They include the following:

1. Poor initial planning
2. Lack of clear objectives and deliverables
3. Lack of understanding of dependencies
4. Inadequate resource allocation
5. Poor risk analysis
6. Poor change management
7. Lack of 'buy-in' from stakeholders
8. Poor understanding of priorities

Their findings are germane to any discussion on defense industry project management. The technology, complexity, large budgets, and multiple stakeholders in the aerospace defense industry projects mirror the problems and challenges of the DoD aerospace acquisition programs. Thus, Lawrence and Scanlan's posits serve as a great foundation for discussion of project terminations within the DoD.

***The technology, complexity, large budgets, and multiple stakeholders in the aerospace defense industry projects mirror the problems and challenges of the DoD aerospace acquisition programs.***

Research into project management conducted by Mir and Pinnington (2014) illustrates the dynamic relationships and interactions of successful project management factors. They test the relationship between project management performance and project success. They concluded that a positive correlation exists between project management performance and contributing variables of project success. The project management performance variables (Mir & Pinnington, 2014) included:

1. Project efficiency
2. Impact on customer
3. Impact on project team
4. Business success
5. Preparing for future

Project success factors included:

1. Project manager leadership
2. Project manager staff
3. Project manager policy and strategy
4. Project manager partnerships and resources
5. Project manager life cycle management processes
6. Project manager key performance indicators

Their research clearly showed that dynamic relationships exist between the factors. When considering project management factors, a context of dynamic relationships must be considered. Factors are not static; each factor or variable in a project dynamically influences other factors.

Research conducted by Allen, Alleyne, Farmer, McRae, and Turner (2014) on project success highlights some of the factors and issues surrounding program success and failure. Using case study analysis as the rubric to identify project success factors, they studied the U.S. Coast Guard's 123-Foot Patrol Boat and Proctor and Gamble's New Growth factory (Allen et al., 2014). The researchers also developed a survey and administered the



survey to project managers involved in the respective projects. Based on the case studies and the associated survey, they concluded that the following factors influence project success (Allen et al., 2014):

1. Project management plan
2. Responsibility assignment matrix
3. Budget monitoring
4. Schedule monitoring
5. Insufficient stakeholder engagement
6. Broad scope and requirements
7. Product monitoring

They also concluded that these factors are excellent tools for analysis on large and small projects (Allen et al., 2014).

*The Defense Acquisition University Smart Shutdown Guidebook* (DAU, 2009) provides tremendous insights into factors that lead to program success or failure that eventually lead to termination. The guidebook specifically lists the following factors:

1. Changes in threat environment
2. Technology changes
3. Changes in budget environment
4. Unsustainable cost growth in development, production, or deployment
5. Failure to meet key performance parameters
6. Policy changes that affect system deployment
7. Selection of alternative approaches to mission requirements
8. Shifting executive authority from one Service to another Service
9. Other programmatic factors



These factors along with other factors identified in the literature review serve as a good basis for analysis of the most influential factors for program termination.

Although the literature identified other factors that affect program success, failure, and termination, the authors chose to limit the scope of analysis of this research to the factors that were most common in multiple works of the literature review. Table 2 summarizes the findings and conclusions of these and other researchers on the topic of factors influencing the outcomes of acquisition programs.



TABLE 2. 11 LEADING FACTORS THAT INFLUENCE PROJECT FAILURE

Attributes/Factors	Sources
<b>Factor 1: Schedule-Related Attributes</b>	
plan schedule management, defining activities and establishing milestones, sequencing activities, low-speed decision making, unrealistic duration, delays in work approval, consistent and compressed schedule pressure, inability to consider ramp-up time	de Wit (1988); Doloi (2013); Fogarty (2010); Fox & Miller (2006); Frimpong, Oluwoye, & Crawford (2003); Mulcahy (1999); Project Management Institute (2008)
<b>Factor 2: Budget-Related Activities</b>	
cost management plan, budget/cost estimation, budget determination, controlling costs, size of budget, estimating activity resources, managing cash flow, contractor financial difficulties	de Wit (1988); Doloi (2013); Fox & Miller (2006); Frimpong et al. (2003); Lawrence & Scanlan (2007); Pinto & Prescott (1988); Pinto & Mantel (1990); Pinto & Slevin (1987); Project Management Institute (2008)
<b>Factor 3: Scope/Requirements-Related Attributes</b>	
vagueness in scope, plan scope management, requirements management plan, requirements collection, defining scope, well-defined work breakdown structure, client-initiated requirements changes, inadequate scope/requirements definition process, failure to curtail scope/requirements creep, lack of understanding the significance of operational environment	Clarke (1999); de Wit (1988); Doloi (2013); Fogarty (2010); Fox & Miller (2006); Frimpong et al. (2003); International Project Leadership Academy (2016); Kappelman, McKeeman, & Zhang (2006); Lawrence & Scanlan (2007); Mulcahy (1999); Pinto & Mantel (1990); Pinto & Prescott (1988); Pinto & Slevin (1987); Project Management Institute (2008); Sage & Rouse (2014)
<b>Factor 4: Project Management Team-Related</b>	
capability of firms, capability of DoD team, anticipation of design changes, delays in receiving instructions, positive attitudes of participants	Belassi & Tukul (1996); Chan & Kumaraswamy (1997); Doloi (2013); Fogarty (2010); Fox & Miller (2006); Frimpong et al. (2003); Hicks (1992); Kerzner (1987); Mansfield, Ugwu, & Doran (1994); Pinto & Mantel (1990); Project Management Institute (2008)
<b>Factor 5: Contract-Related</b>	
type of contract, inaccurate estimates in contract, form of procurement and contractual agreements, poor contract management, contract negotiation	de Wit (1988); Doloi (2013); Frimpong et al. (2003); Project Management Institute (2008); Shehu & Akintoye (2010)

TABLE 2, CONTINUED

Attributes/Factors	Sources
<b>Factor 6: Planning Attributes</b>	
not developing a thorough plan, lack of planning buy-in by all, informal plan for change requests, underestimating complexity of project, planning deficiencies, coordinating ability, rapport between participants, selection of program managers	de Wit (1988); Fox & Miller (2006); International Project Leadership Academy (2016); Kappelman, McKeeman, & Zhang (2006); Kerzner (1987); Lawrence & Scanlan (2007)
<b>Factor 7: Stakeholder Engagement</b>	
identifying key stakeholders, stakeholder management plan, controlling stakeholder engagement, considering project from stakeholder perspective, failure to get stakeholder buy-in on major decisions, lack of communication between stakeholders	Fogarty (2010); International Project Leadership Academy (2016); Kerzner (1987); Pinto & Mantel (1990); Pinto & Slevin (1987); Project Management Institute (2008); Sage & Rouse (2014)
<b>Factor 8: Risk Mitigation</b>	
risk management, performing qualitative risk assessment, performing quantitative risk assessment, planning risk responses, controlling risks, inability to anticipate problems	Clarke (1999); Doloi (2013); Fox & Miller (2006); Frimpong et al. (2003); International Project Leadership Academy (2016); Mulcahy (1999); Pinto & Prescott (1988); Project Management Institute (2008)
<b>Factor 9: Communication-Related</b>	
communication between project management team members and communication to stakeholders	International Project Leadership Academy (2016); Project Management Institute (2008)
<b>Factor 10: Technology Readiness Level (TRL)</b>	
TRL level, shortages of technical personnel, delays in testing	Mankins (2009); Straub (2015)
<b>Factor 11: Contractor-Related</b>	
inadequate contractor experience, lack of communication between contractor and DoD, subcontractor projects, low labor productivity, poor procurement programming	Doloi (2013); Frimpong et al. (2003); Project Management Institute (2008)

## Research Aim and Objectives

This article analyzes and evaluates the causes of acquisition program and project failure within the DoD. The objectives of this article are:

- To study, identify, and evaluate the most critical factors that influence program and project termination within DoD;
- To evaluate the main factors, based on expert judgment, that lead to program and project failure, and the relative importance of those factors;
- To identify any differences between DoD acquisition program managers, DoD contractors, and DoD consultants; and
- To serve as a springboard for future research in DoD program and project management.

The purpose of this research is to expand the current understanding of program and project failures and successes, and to identify the different perspectives between various stakeholders within the acquisition program and project management enterprise at the aggregate level. Although significant research has been conducted on terminated programs within the DoD, the research has focused on individual programs or a group of select programs. The Federally Funded Research and Development Centers, GAO, and Congressional Research Service normally evaluate a specific program or a small group of programs.

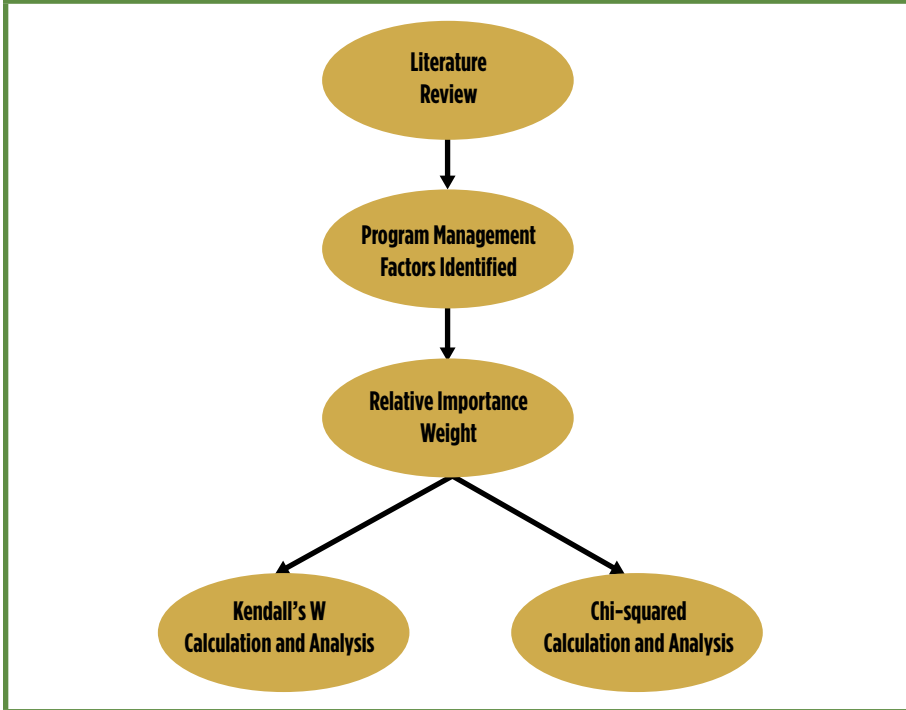
However, the authors could find neither a robust comprehensive study based on expert judgment (the approach used in this research) in the literature, nor the analytical approach used in the text for analysis of DoD program and project terminations.

## Methodology

For this study, the examination and methodology used a literature review to identify factors that lead to program and project success or failure, expert judgment, survey, relative importance weight, and Chi-squared distribution to analyze the factors identified in the literature review. Relative Importance Weight (RIW) methodology consisted of conducting a survey to identify and evaluate the relative importance of the significant factors influencing program termination (see Figure 4 for methodology flow). Respondents of this survey included the following three groups: (a) DoD

program and project managers, (b) DoD industry personnel, and (c) DoD consultants. If respondents did not fall into one of these groups or had no experience with program and project termination, their responses were not considered. The 131 participants of a structured survey were identified through professional networks, Project Management Institute events, and National Defense Industrial Association events.

**FIGURE 4. METHODOLOGY FLOW DIAGRAM**



To gather data for evaluation, analysis, and comparison of program and project failure factors within the DoD program portfolio, a questionnaire was developed seeking respondents from three specific groups: program managers from the Services, program managers from companies with past experience working on DoD programs, and DoD program managers. The questionnaire consisted of 11 leading factors that influence project failure, extrapolated from an extensive literature review. The factors evaluated are outlined in Table 2. The literature review indicated that commonality existed between project success and failure factors. The success or failure factor depended on the author's point of view. Essentially, program success and failure factors are two sides of the Janus coin. In the context of this

text, program and project failure is defined by program termination. The factors identified in the literature influence program performance and thus influence program termination.

A total of 131 responses was analyzed, which consisted of 45 DoD program managers, 52 defense industry program managers, and 34 defense industry consultants. Based on previous research (Doloi 2008; Flyvbjerg, Holm, & Buhl, 2004), these numbers are acceptable for this type of analysis. Further, since these data are ordinal and thereby nonparametric, many opinions exist on what constitutes an appropriate sample size (Bonett & Wright, 2000; Noether, 1987). The various works on estimating an appropriate sample size rely on assuming some degree of normality. To be confident in the sample size, but maintain the integrity of the nonnormality of the nonparametric data, a sample size of 30 was an appropriate sample for the three groups.  $N=30$  is recognized in many statistical works as an agreed-upon acceptable sample size (Devore, 2012; Sprent, 1989). Table 3 identifies the profiles of the respondents.



TABLE 3. RESPONDENTS' PROFILES

	Number of Responses Used	Average Experience (Years)	Average Project Budget (Millions)
DoD Program Managers	45	>10	>100
DoD Defense Industry Program Managers	52	>5	>100
DoD Consultants	34	>10	>100

Respondents were asked to rate the relative importance of the factors that influence project failure based on a five-point Likert Scale (1 = very low, 2 = low, 3 = medium, 4 = high, 5 = very high). To differentiate the expert perceptions of the relative importance of project failure between groups, two hypotheses were developed and tested:

- $H_0$ : There is no agreement among groups of the relative importance of factors that influence program/project failure.
- $H_1$ : Agreement exists among groups of the relative importance of factors that influence program/project failure.

## Findings and Data Analysis

For analysis of responses, RIW analysis was conducted (Doloi, 2013; Frimpong et al., 2003). RIW is a weight measure to compare the importance of various attributes according to a group of respondents. Weights must be assigned to a collection of survey responses; if the survey responses are numerical already, and ordered such that the “most important” response is assigned the highest value (such as the Likert scale), the numerical assignment comes directly from the survey results. The RIW for responses was calculated using the following equation (Salunkhe & Patil, 2013):

$$RIW = \frac{\sum_{i=1}^5 a_i n_i}{\sum_{j=1}^N x_j} \times 100 \quad (1)$$

Relative Importance Weight

$RIW_j$  = the relative weight important for attribute j

$a_i$  = the weight given to response (Likert is used, therefore  $i = 1,2,3,4,5$ )

$n_i$  = the number of people who responded “ $i$ ” for attribute  $j$ .

$x_j$  = is the sum of all weighted responses for the  $j$ th attribute.

$N$  = total number of factors

The RIW equation was used to calculate the RIW for program and project failure factors. The weights were ranked for DoD program managers and DoD contractors. The results of the weights are shown in Table 4.

TABLE 4. SUMMARY OF RIW RESPONSES						
Ratings/Rankings						
Factors	DoD Program Managers		DoD Industry Program Managers		DoD Consultants	
	RIW Score	Rank	RIW Score	Rank	RIW Score	Rank
Schedule-Related	12.86%	1	11.71%	3	1	11.66%
Budget-Related	10.61%	2	12.53%	1	2	11.19%
Scope-Related	10.54%	3	11.95%	2	4	9.34%
Project Management Team-Related	6.15%	11	6.15%	11	11	6.94%
Contract-Related	6.64%	10	6.34%	10	5	8.97%
Planning-Related	8.26%	8	10.32%	4	6	8.70%
Stakeholder Engagement-Related	9.47%	5	8.26%	8	7	8.33%
Risk Mitigation-Related	9.13%	7	8.67%	7	9	7.86%
Communication-Related	6.74%	9	6.74%	9	10	7.77%
Technology Readiness Level-Related	10.43%	4	9.13%	6	8	8.14%
Contractor-Related	9.16%	6	9.16%	5	3	11.10%

To determine if there was a significant difference between the rankings of the three groups’ responses, Kendall’s Coefficient of Concordance served as the analytical tool. Kendall’s coefficient of concordance, or Kendall’s  $W$ , is a nonparametric statistic, recognized as an analytical tool appropriate for assessing the degree of agreement among judges. Kendall’s  $W$  ranges from 0 to 1 (Grzegorzewski, 2006). A rating of zero indicates no agreement and a rating of one indicates strong agreement (Hollander, Wolfe, & Chicken, 2014):



$$W = \frac{12S}{m^2 (n^3 - n)}$$

*m* = total number of judges (respondents)

*n* = total number of objects (factors)

$$S = \sum_{i=1}^n (R_i - \bar{R})^2$$

$$R_i = \sum_{j=1}^m (r_{ij})$$

$$\bar{R} = \frac{1}{n} \sum_{i=1}^n R_i$$

Based on the responses from Table 4, Kendall’s *W* = 0.84. This strongly suggests that agreement exists among the three groups. Despite this strong evidence of agreement, a Chi-squared approximation was also conducted to validate the results. The Chi-squared equation is shown here, followed by Table 5.

$$\chi^2 = m(k - 1)$$

(Devore, 2012)

*k* = number of factors

TABLE 5. RESULTS TABLE	
<b>k</b>	11
<b>m</b>	3
<b>W</b>	0.84848
<b>r</b>	0.77273
<b>χ<sup>2</sup></b>	25.4545
<b>df</b>	10
<b>p-value</b>	0.00455

Based on the Chi-squared equation, the calculated value of Chi-squared was 25.45. Using the critical value for Chi-squared for *k* = 11, degree of freedom = 10 with significance = .01, the critical value of *χ<sup>2</sup>* was calculated as follows:

$$\chi_{.05}^{2(n-1)} = \chi_{.05}^{2(10)} = 18.3$$

Since  $25.45 > 18.3$ , reject the null hypothesis. Further, for a level of significance  $\alpha = .01$ , p-value .0045 is less  $\alpha = .01$ , reject the null hypothesis. The results indicate that a significant level of agreement exists among DoD program managers, DoD industry program managers, and DoD consultants.

## Results Discussion

The survey was analyzed from the DoD program manager, DoD consultant, and DoD industry program manager's perspective. RIW analysis illuminated the factors that have the greatest influence on program termination from the various groups' perspectives. Table 4 displays the rankings by the various groups.

***DoD program managers and defense industry program managers agreed on the top three factors that influence program termination: schedule-related attributes, budget-related attributes, and scope-related attributes.***

Since the data analysis indicates that agreement exists among the various groups, the leading factors present opportunities to address. The analysis indicates that several factors greatly influence program termination. DoD program managers and defense industry program managers agreed on the top three factors that influence program termination: schedule-related attributes, budget-related attributes, and scope-related attributes. DoD consultants ranked schedule-related attributes and budget-related attributes one and two respectively, but contractor-related attributes was the other top three factor.

The data also indicate that program and project management team-related attributes was the least most important factor by all groups. This suggests that strong agreement exists among the groups that program and project management teams put forth great effort to ensure program success. This also infers that program managers have the right tools and understanding of acquisition systemic processes to be successful.

## Recommendations

Based on the analysis discussed previously, the authors offer several recommendations for consideration since the experts agree that several attributes influence DoD program termination:

- DoD should continue investment into understanding the root causes of schedule-related attributes.
- Realistic, adequate, and appropriate fiduciary requirements must be established early in the programming process to ensure program success.
- DoD should continue investment in understanding requirements creep in programs.
- Since DoD consultants ranked contractor-related attributes extremely high, and DoD program managers and DoD industry program managers rated contractor-related attributes relatively high, this area warrants further research to explore and perform a root cause analysis of contractor-related attributes.
- The DoD's investment in program manager training and equipping program managers should be continued.

Implementation of the recommendations should have a positive influence on DoD acquisition program performance.

## Study Limitations

The research presented in this article has two limitations that should be considered when digesting the findings. First, this study was performed at the aggregate level within the DoD. DoD survey participants represented all branches of the Services and DoD program managers. Perspectives from the different Services were not considered, but rather the DoD aggregate. Although the Services have very similar experiences in program and project cancellation, the nuances of the differences in the importance of factors is worth mentioning and exploring in future research. Another limitation of the research is the mode chosen for factor analysis. The researchers presented and selected the factors for analysis to be presented to survey participants. Although the factors were determined from an exhaustive literature review, an open-ended survey may have presented a new set of factors for analysis and consideration unique to DoD program and project

management. Further, the researchers limited the factors for analysis, thereby excluding some factors from the literature. However, the factors selected for analysis were the factors most common across multiple authors and articles.

Another limitation of the research is further root cause analysis of the factors identified, surveyed, and analyzed. Root cause analysis of the factors would provide greater fidelity and granularity of the factors. This fidelity and granularity could lead to plausible solutions and corrective actions to address the influence of these factors on DoD acquisition program termination. The authors chose to first focus on identifying DoD acquisition program factors and determining whether agreement existed among the three prominent DoD acquisition groups. The authors recommend that future studies should focus on the root cause analysis of the factors identified.

## Summary and Conclusions

This research identified the RIW of factors that influence DoD program termination. Factors were identified through a literature review of salient research on factors that lead to program success and failures. These factors served as the basis for analysis into DoD acquisition program termination. A survey was developed from the factors garnered from the literature review to determine the RIW of each of the factors. The survey was administered to DoD acquisition program managers, DoD industry program managers, and DoD consultants. The three groups' responses were compared. The results showed that there is agreement among the three groups on the influence of the factors analyzed. Based on the analysis of the results, the authors presented several recommendations for the DoD acquisition enterprise. This agreement suggests that there are opportunities and areas for the groups to work together to mitigate the most important factors, thereby decreasing the likelihood of program termination.

## Areas for Future Research

In a similar vein as the study limitations, the authors recommend several areas for future research. First, this study did not consider the role of the Congress in DoD acquisition program cancellation. In the United States, Congress plays a huge role in program termination. Congress has the power to cut program budgets, terminate programs, conduct hearings on program status, and change requirements. Often, the DoD wants to cut

a program, but Congress orders the programs to continue. As mentioned in the study limitations, an open-ended survey could produce an entirely new set of factors or attributes for consideration or analysis unique to DoD programs. Once these new factors are identified, a host of data analysis could be performed including, but not be limited to, dynamic interactions of these new factors, attribute and factor analysis, and RIW. This study identified the most important factors. Future research could focus on the why of the most critical factors that are unique to the DoD. Another area for future research could focus on the derivatives of failed and canceled programs. Although programs are canceled, a resultant loss is not always incurred. The derivatives, vestiges, and lessons learned from those programs suggest that all is not lost. Putting a value on these aspects could be beneficial in program analysis or termination. For example, the Army Future Combat System was terminated. On the surface and aggregate, this may appear like a failure, but many of the technologies and systems developed were used in other Army systems. All was not lost despite program failure and termination. A comparison of successful and failed DoD programs is another area for future research. This research could compare the root causes in the difference between successes and failures. A final area for future research is the role of knowledge management in program and project failure.

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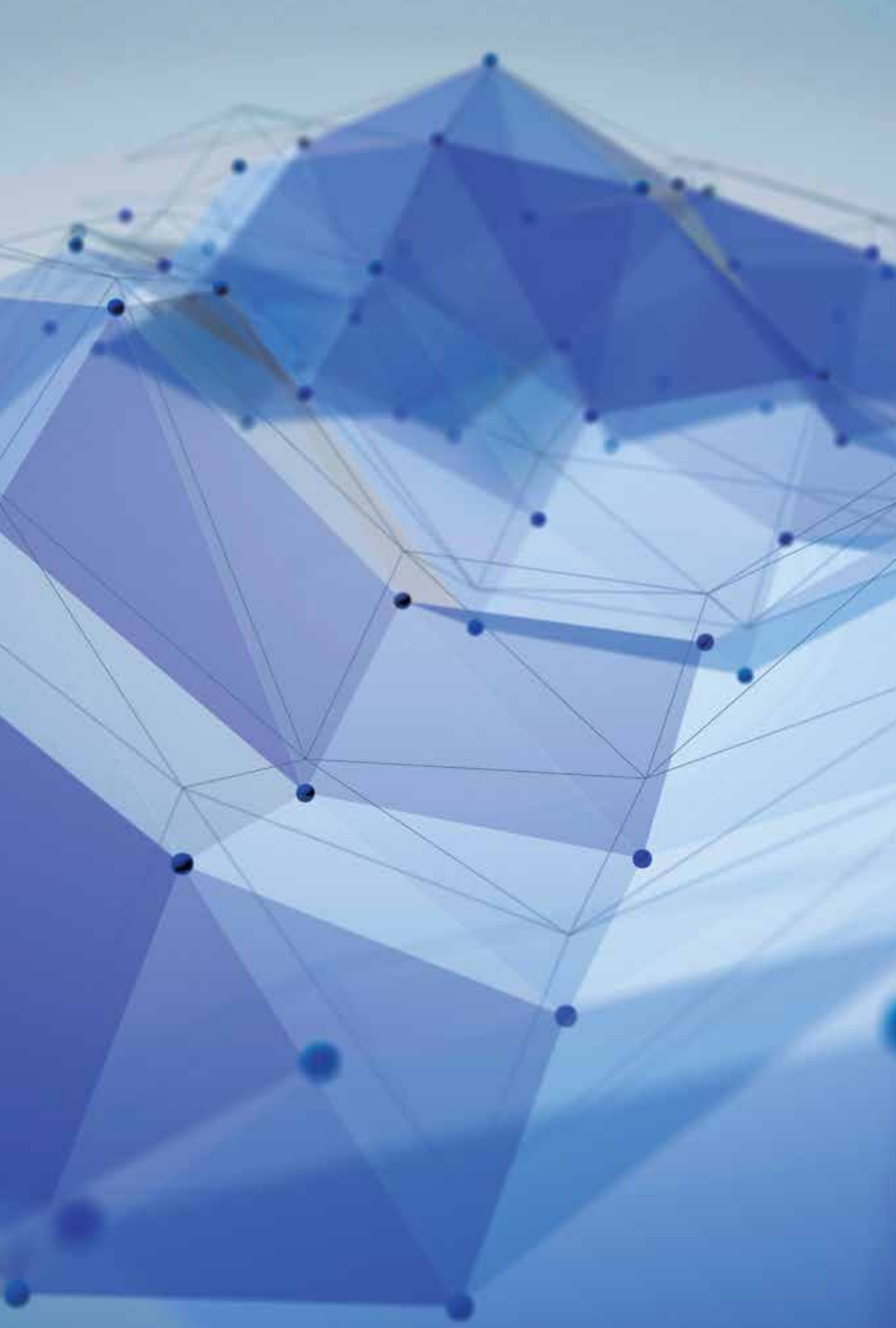
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# Wartime Construction **PROJECT OUTCOMES** as a Function of **CONTRACT TYPE**

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Lt Col Peter Feng, USAF, and Edward White*

The United States has spent more than \$23 billion on construction in Afghanistan since 2001. The dynamic security situation created substantial project uncertainty, and many construction projects used cost-plus-fixed-fee contracts (CPFF) instead of the firm-fixed-price (FFP) norm. Using a dataset of 25 wartime construction projects managed by the Air Force Civil Engineer Center, the authors sought to confirm that both contract types yield project outcomes consistent with the established literature. As expected, they found CPFF contracts had greater cost and schedule growth than FFP. However, they did not find differences regarding as-built quality. Additionally, the authors sought to determine whether CPFF contracts exhibited greater construction risks than FFP contracts. They found no significant differences between contract types in terms of security incidents or other environmental factors. This research may be particularly relevant to military owners who contract projects in wartime environments.

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**Keywords:** *firm-fixed-price, cost-plus-fixed-fee, Afghanistan, construction management, contract structure*

## Background

Contracts should allocate risk to the contracting party best able to manage the risk. According to McInnis (2001), risk in the construction industry has been categorized into two divisions: contractual risk and construction risk. Contractual risks include items such as miscommunication, lack of contract clarity, or poor contract administration. They are internal to the contract and occur because an imperfect owner and imperfect contractor have chosen to work together. Construction risk includes items such as weather, resource availability, and acts of God. In contrast to contractual risk, construction risk is external to the contracting parties and would exist even if the parties were perfect (McInnis, 2001). Risk allocation is especially important in a wartime construction environment. Contractors working on behalf of the U.S. mission in Afghanistan faced a host of risks, including security threats, long logistical chains, extreme weather, and a lack of qualified personnel (Recurring Problems in Afghan Construction, 2011). As the owner, the U.S. Government managed and allocated the risk through contract type choices. Using the lens of contract types employed in Afghanistan, namely fixed-price and cost-reimbursable contracts, this article seeks to understand better the differences in contractor behaviors across contract types in a wartime construction environment.

The default contract type for federal construction services is a firm-fixed-price (FFP) contract (Federal Acquisition Regulation [FAR], 2015, pt. 36.207). Contracting officers are responsible for contract type determinations, but they are aided by the FAR decision framework. Contracts with well-established specifications that allow both the government and prospective bidders to estimate costs accurately should be FFP contracts (FAR, 2015, pt. 16.104; Scherer, 1964); such contracts place the maximum amount of construction risk on the contractor and should also provide the contractor with higher profit expectations (Scherer, 1964). Construction contracts typically are reasonably well defined. Thus, FFP contracts should be used.





A cost-plus-fixed-fee (CPFF) contract is the opposite of an FFP contract. The government assumes all risk for allowable costs up to the extent prescribed in the contract (FAR, 2015, pts. 16.301–1). Under this contract type, the government and contractor agree to a fee that is fixed at the inception of the contract and based on an estimate of total costs rather than final costs (FAR, 2015, pt. 16.306). The estimate is not binding, and the true cost is flexible up to the allowed maximum amount (Scherer, 1964). Unless significant uncertainty or risk is involved in the project, CPFF contracts should not be used in federal procurement (FAR, 2015, pts. 16.301–2). Because the government bears the risk of the uncertain environment, these contracts have significantly weaker cost-efficiency incentives (Scherer, 1964); consequently, they are typically used only for preliminary and exploratory studies as a precursor to FFP contracts (FAR, 2015, pt. 16.306).

An incentive contract is a third type of contract that lies between the polar opposites of FFP and CPFF contracts. This contract type allows owners to reward contractors for meeting specific cost, delivery, or performance goals (Bower, Ashby, Gerald, & Smyk, 2002). According to the FAR (2015,

pt. 16.401), incentive contracts may be used when FFP contracts are not feasible and the government needs options to motivate the contractor to improve delivery efficiency and minimize waste. The contract type allows owners to share risk more evenly with contractors. Incentive contracts have increased in popularity in the private construction sector (In't Veld & Peeters, 1989). Yet, their actual usage remains low in absolute terms. The literature suggests that owners will generally use either FFP or CPFF contracts for construction services (Bajari & Tadelis, 2001).

From 2002 to 2013, the United States spent more than \$23 billion on wartime construction efforts in Afghanistan (Johnson, 2014, p. 2). Contractors building and repairing infrastructure and facilities on behalf of the U.S. Government faced a different and unique environment when compared to peacetime construction. This environment included Taliban attacks that killed or injured workers and destroyed equipment (Affleck, Seman, Deegan, Freeman, & Sargand, 2011; cf. *Tawazuh Commercial and Construction Co. Ltd. v. United States*, 2011), a remote and problematic supply chain (Boon, Huq, Lovelace, 2011; cf.



*Water Reclaim Systems Inc. v. United States*, 2008), and a harsh physical environment (Affleck et al., 2011). The environment was deemed sufficiently uncertain that the U.S. Government's contracting officers elected to use a combination of FFP and CPFF contracts to support U.S. construction requirements.

***While cost reimbursable contracts may entice companies to submit bids, they also provide a significant possibility for cost growth and will need to be monitored differently than fixed-price contracts.***

We seek to expand the body of knowledge regarding contract types in wartime construction. This research may be particularly relevant to military owners who contract construction projects in wartime environments. While cost reimbursable contracts may entice companies to submit bids, they also provide a significant possibility for cost growth and will need to be monitored differently than fixed-price contracts. Conversely, fixed-price contracts in wartime environments may shift so much risk on contractors that it is impossible for companies to make a profit, leading to higher prices due to a lack of competitive bids or a reduction in project quality. Therefore, this research effort used data from 25 Afghan wartime construction projects to search for factor differences between fixed-price and cost-reimbursable projects. These projects were funded by the U.S. Government in support of the NATO Training Mission-Afghanistan, with the Air Force Civil Engineer Center (AFCEC) serving as the construction agent (i.e., the entity responsible for contract administration, including quality assurance). While the Afghan government took ownership after contract close out, the U.S. Government was the owner during contract administration. We seek to answer two investigative questions in this study:

1. Do CPFF and FFP wartime construction contracts yield project outcomes consistent with the established (peacetime) literature?
2. Given that CPFF contracts should be used in uncertain circumstances, did CPFF contracts exhibit greater construction risks than FFP contracts?

## Literature Review

The underlying theory of contract behavior based on contract types has been well established. The theory of contractual incentives promulgated by Sherer (1964) established expected contractor behaviors using a maximization problem. The theory focuses on expected contractor behaviors in incentive contracts (cf. Federal Acquisition Regulation, 2015, pt. 16.401) that lie between the polar choices of FFP and CPFF, yet it also informs our understanding of contractor behaviors in FFP and CPFF contracts. For all contract types, a contractor's profit,  $\pi_C$ , can be determined by using the following equation, where  $\pi_T$  equals the target profit amount,  $\alpha$  equals the cost-sharing coefficient,  $C_T$  is the negotiated target cost, and  $C_A$  is the actual cost charged to the contract.

$$\pi_C = \pi_T + \alpha(C_T - C_A)$$

For FFP contracts  $\alpha$  will equal one, and for CPFF contracts  $\alpha$  will equal zero. Simplifying the equation, we see that a contractor's expected profit for FFP contracts is its negotiated target amount plus its bid price minus actual costs. In contrast, for CPFF contracts, a contractor's expected profit is only the negotiated target amount (which may increase through the negotiation of added work). Hence, it is widely known that there are weak cost-saving incentives for CPFF contracts.

The negotiated target amount,  $\pi_T$ , is a function of financial risk. When the contractor bears additional financial risk, such as in an FFP contract, the negotiated target amount will be higher. When the contractor has negligible risk, as in the case of CPFF, the target amount will be lower (Scherer, 1964).

Shearer's (1964) study notes several key contractor behaviors. First, for established projects, where the risk can be managed, contractors should prefer FFP contracts as they have higher potential profit margins for the contractor. Second, as project uncertainty increases, contractors prefer CPFF contracts over FFP, at the expense of higher profit margins; CPFF contracts shield contractors from potential losses due to the uncertainty. Last, because FFP contractors bear the risk for actual costs,  $C_A$ , if contractors encounter unexpected risk, actual costs can be reduced by cutting quality, letting the schedule slip, or eliminating personnel.

Bajari and Tadelis (2001) have proposed a complementary theory that views the contract-type decision in terms of postaward adaptability instead of preaward superior knowledge. They note that FFP contracts can reduce initial costs, but those cost savings can be lost through contract

modifications. Cost savings are lost because the FFP contract compensation scheme is based on specific delivery requirements agreed to within the contract. While the contract allows for changes, implementation of the changes requires the compensation to be renegotiated. In contrast, CPFF contracts have a well-defined compensation scheme for both the initial design and subsequent changes. Awarding a contract modification does not require renegotiation. The postaward adaptability also implies that less conflict (or friction) will be observed between the owner and the contractor with CPFF contracts. Uncertainty also plays a central theme in Bajari and Tadelis's model. For projects with little or no uncertainty, FFP contracts will be preferred; for projects with high uncertainty, CPFF contracts will be preferred. The model suggests that complex projects should be acquired using CPFF contracts to allow greater adaptability to the inherent design changes; in contrast, simpler projects should be acquired using FFP contracts to provide cost savings to the owner.

***The literature is clear that as project requirement uncertainty increases, owners should consider the use of cost-reimbursable contracts.***

The empirical evidence within the literature largely supports these two theories. FFP contracts should be used for well-defined projects and CPFF contracts for projects with more uncertainty (Adler & Scherer, 2011; In 't Veld & Peeters, 1989; Müller & Turner, 2005; von Branconi & Loch, 2004; Wamuziri, 2013). First, von Branconi and Loch (2004) and Müller and Turner (2005) discussed the term project uncertainty, i.e., the project's degree of risk, using the framework of owner involvement. Those authors observe that owners tend to be less involved during FFP construction, which can lead to perceived poor outcomes. Because the project requirement is expected to be well defined, an owner's failure to apply sufficient diligence in defining the requirement may lead to an outcome that does not meet quality expectations. Von Branconi and Loch (2004) and Müller and Turner (2005) also note that with CPFF contracts, the project is ill-defined by definition. The lack of definition compels the owner to be more involved, resulting in physical outcomes that typically meet expectations. As is often the case, if costs are not controlled, CPFF will have higher costs. Adler and Scherer (2011) view the uncertainty difference in terms of knowledge. If the contractor can apply superior knowledge in support of the contract requirements, CPFF contracts

are preferred; otherwise, FFP contracts should be used. Lastly, In 't Veld and Peeters (1989) examined which categories of construction uncertainty should sway the contract type decision. They found that FFP contracts were an appropriate mechanism for contractors to manage risk from resource availability, schedule criticality, and performance requirements. However, if the risk is due to cost uncertainty or technical uncertainty, cost-reimbursable contracts should be used. The literature is clear that as project requirement uncertainty increases, owners should consider the use of cost-reimbursable contracts

Scherer's theory as it relates to cost performance and quality has largely been substantiated in recent work investigating construction contracting. Wamuziri (2013) found that negotiated target amounts are indeed higher for FFP construction projects. Additionally, he found CPFF contracts to have higher overall costs. Jaskowski (2012) conducted the only wartime comparison of contract types that we were able to locate. She found that FFP contracts had less schedule growth, CPFF contracts produced better quality facilities, and there was no cost growth difference between the two. While the study had a small sample size, the results are generally consistent with previous literature, with the exception that she did not observe cost growth differences.

In summary, the literature suggests three primary performance differences between FFP and CPFF contracts. First, on average, FFP contracts will have less cost growth than CPFF contracts. Second, FFP contracts will have less schedule growth than CPFF contracts. Lastly, FFP contracts will be of lesser quality than CPFF contracts. These three factors—time, cost, and quality—form the project management iron triangle and are known to influence one another (Ika, 2009).





Given these performance outcomes as indicated by the literature, we next will discuss how wartime construction may differ from peacetime construction and suggest ways in which the performance differences may be affected. Wartime projects likely face the same risks as peacetime projects, with some notable additions. The U.S. Army Corps of Engineers (USACE) commissioned a study to document construction challenges in Afghanistan (Affleck et al., 2011). Many of the risks observed by the USACE are not unique to wartime—they are common in other nearby Asian and African countries and include design problems, planning problems, weather interference, unskilled workers/quality problems, difficulty working with the owner or lack of direction from the owner, and change orders or scope changes (Affleck et al., 2011; Assaf & Al-Hejji, 2006; Mansfield, Ugwu, & Doran, 1994; Marzouk & El-Rasas, 2014; Olima & K'akumu, 1999).

The Afghanistan Study found that security concerns were overwhelmingly the primary challenge to projects (Affleck et al., 2011). This factor is unique to wartime projects. However, the FAR contains provisions for security. It defines acts of God (weather) and acts of the public enemy (hostile or criminal acts) as excusable delays (FAR, 2015, pts. 52.249–14; Kelleher, Walters, Smith, Currie, & Hancock, 2009). Also, while not required by the FAR, it was common practice to require contractors to carry insurance to cover the loss of equipment stemming from criminal or hostile acts. Additionally, many contracts required contractors to provide their own security, because U.S. military and Afghan Security Forces did not provide active security for construction projects (*Tawazuh Commercial and Construction Co. Ltd. v. United States*, 2011). In the context of contract types and risk allocation, the contracts treated the security as a valid construction risk.

In assessing the resulting risk, arguments can be made for classifying a project as either an FFP or a CPFF contract. One argument for continuing to classify construction as FFP is that the project specifications do not change as a result of possible attacks. Technical uncertainty would remain the same (In 't Veld & Peeters, 1989). However, using the cost uncertainty argument (In 't Veld and Peeters, 1989), one could argue that security risks will cause





more cost uncertainty. Even when the company is insured against the loss of personnel or equipment, the cash needed to continue the project could be at risk while the claim is adjudicated. Without sufficient cash to continue material acquisition and payroll requirements, a project could be halted while it is made whole. Thus, it is reasonable to use a CPFF contract to cope with cost uncertainty.

The physical environment of the project is commonly mentioned in both wartime and peacetime literature. Weather conditions are one of the most commonly cited delay factors for all projects. Afghanistan has the potential for particularly harsh weather, especially in the mountainous regions. Affleck et al. (2011) stated that planning for harsh weather was particularly poor in Afghanistan. Other industry literature does not discuss planning, but does consistently cite weather as a cause for delay. Most construction contracts allow for a certain number of weather delay days, but also state that it is considered an excusable delay, offering no compensation except in extreme cases (Kelleher et al., 2009). As the literature notes, schedule criticality can be effectively managed with FFP contracts (in 't Veld & Peeters, 1989). Notwithstanding the harsh environment, there is no compelling argument for CPFF contracts instead of FFP contracts.

## Methodology

To understand how contract types affect project outcomes (i.e., schedule, cost, or quality) in wartime construction projects, the Mann-Whitney median comparison test was used to test differences among the median for project factors and performance factors (Table 1). The project factors are basic metadata relating to cost and schedule performance for each project, such as award, contract length, and the number of contract modifications. Performance factors relate to quality performance: the major construction, design, and material quality control deficiencies cited by the quality assurance engineer, as well as worker health and safety compliance. Note that within Table 1, the performance factors are subdivided by major construction elements and represent observed deficiencies by government quality assurance (QA) engineers. As the FAR contains clauses to accommodate contingency construction, we expect to see project outcomes similar to those described by the literature.



TABLE 1. PERFORMANCE ANALYSIS FACTORS	
Project Factors	
	Award Amount Final Cost Awarded Cost Growth (Index) Number of Contract Modifications Number of Change Orders (Scope Changes) Number of FPOP Extensions Total Days Added to the Contract Initial Period of Performance Final Period of Performance Awarded Schedule Growth (Index)
Performance Factors	
Quality Factors	Horizontal Work (concrete and/or asphalt) Building Foundation (concrete/rebar/soils) Electrical (high and low voltage, comm lines/outlets) Mechanical (HVAC, gas, boilers) Utility (water, sewer, and storm) Structural (masonry, steel, and wood) Interior Finishing (doors, tiles, walls, ceilings, bathroom fixtures, paint) Exterior Finishing (windows, exterior doors, garage doors, fences)
Technical Performance Factors	Design Performance Material/Submittals
Health and Safety	Safety Incidents and/or Deficiencies

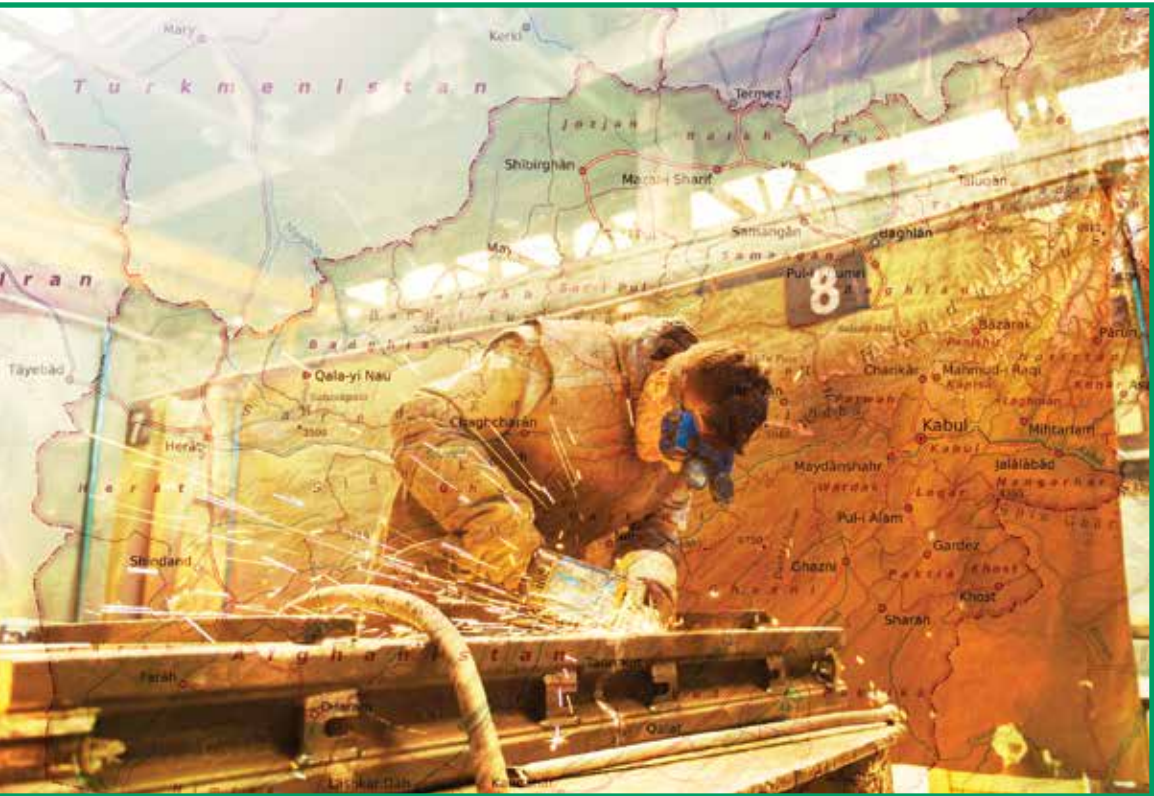
The Mann-Whitney median comparison test was used to test differences among the median for uncertain environmental factors to determine whether FFP and CPFF contracts exhibited similar levels of external construction risks (Table 2). Environmental factors are the external elements of the physical setting that are outside the control of the contractor. Taliban attacks, severe weather, and interference from the Afghan government are examples of external environment factors. We expect that CPFF contracts should have more instances of security or weather challenges to account for the greater construction uncertainty.

TABLE 2. RISK ANALYSIS FACTORS	
External Environmental Factors	
	Region of Afghanistan
	Security Incidents
	Other External Environment Issues
	Weather

The response variables were obtained by analyzing each project’s daily reports, created by the U.S. Government’s QA engineers. Twenty-five projects were analyzed: 11 were FFP, and 14 were CPFF. All projects were managed by AFCEC and were in support of the Afghan Government. Consequently, all projects were considered “outside-the-wire” (i.e., they occurred outside of the guarded perimeter of U.S. military operating locations). Each report contained comments regarding construction quality (positive and negative) as well as daily construction activities (e.g., quality deficiencies, mock-up meetings, progress for each craft). They also documented delays, security incidents, safety mishaps, or deficiencies. The average award cost was \$25.5 million (median was \$17.0 million), and the average final cost of the projects was \$33.2 million (median was 23.9 million). The majority of the projects focused on vertical construction. Table 3 provides summary data regarding the projects.

TABLE 3. PROJECT DATA			
Project Information	Mean	Median	Standard Deviation
Award Amount	\$25.5 M	\$17.0 M	\$21.4 M
Final Cost	\$33.2 M	\$23.9 M	\$28.7 M
Number of Contract Modifications	8.73	7	3.94
Change Orders (Scope Changes)	2.93	2	2.40
Initial Period of Performance (days)	382.76	365	144.82
Final Period of Performance (days)	822.84	741	353.70

The daily quality reports were coded by the factors shown in Tables 1 and 2, yielding the independent variables for this study. When an occurrence of a factor was encountered in the review of the daily reports, the incident was recorded. Each occurrence was independently linked to the project and all of the metadata associated with that project. This linkage allowed for a summary coding for each project, which then allowed for differentiation between projects, based on contract type.



Typically, two samples are compared for differences using a *t*-test; it calculates a mean and standard error based on a significance level for each sample. The standard errors are then compared to see whether the error bands overlap. If they overlap, one can conclude that there is no significant difference between the samples. The *t*-test requires the assumption of normally distributed data. Since our data did not meet this assumption, we used the Mann-Whitney test (also known as the Wilcoxon rank-sum test) to determine whether there were performance differences between the contract types. Conceptually, the main difference between a *t*-test and the Mann-Whitney test is the latter's use of relative values compared to observed values in a *t*-test. In the Mann-Whitney test, the observed values are converted to relative values by rank ordering them from 1 to *n*. A sum-rank score is then calculated that is then converted to a hypothesis test statistic, *U*, and used in a standard *z*-test (Gold, 2007).

If a *t*-test is used and its assumptions are violated, it can cause the analyst to draw incorrect conclusions. Consider the case in which the data are not normally distributed, but contain outliers to the right (i.e., final period

of performance with a mean of 823 days, a median of 741, and a standard deviation of 354). The increased variance from the outliers will increase the standard error and cause the error band to be larger. As error bands grow larger, statistical differences are more difficult to observe. Thus, one could infer there is no difference between the samples when there really is a difference. With the Mann-Whitney test, the influence of outliers is diminished because each observation is compared to other observations relatively; it is a more robust test than the t-test. When the data are normally distributed, the Mann-Whitney test has an asymptotic efficiency of approximately 95 percent when compared to a t-test (Lehmann, 2006).

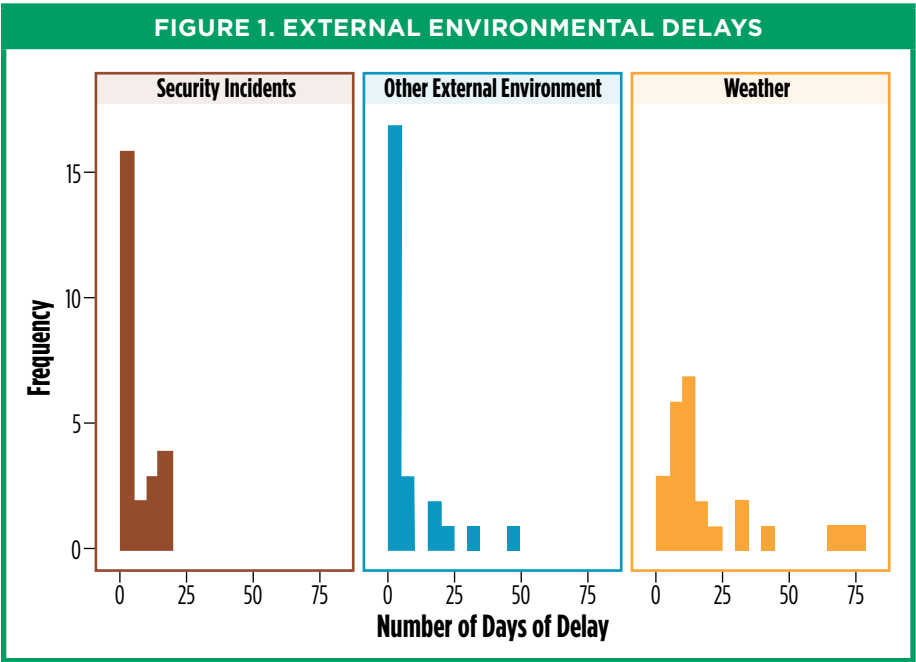
Thus, the Mann-Whitney hypothesis test was used to determine whether the median values for each contract type were statistically different; its solution can indicate whether there is a significant difference in construction outcomes as measured by the average performance of an FFP contract over a CPFF contract. Its application is appropriate for our data, which are not normally distributed.

***Even more than security, the weather was the most commonly reported external environment issue, followed by security incidents, and then by any other external environmental issue, which ranged from locals and the Afghan National Army interfering with the project, to a swine flu outbreak halting progress on several projects for multiple days.***

## Analysis

All of the projects exhibited a significant amount of construction risk. Even more than security, the weather was the most commonly reported external environment issue, followed by security incidents, and then by any other external environmental issue, which ranged from locals and the Afghan National Army interfering with the project, to a swine flu outbreak halting progress on several projects for multiple days. Most projects had fewer than 40 days of weather delays. The maximum number of delay days due to security was 18. However, the majority of the projects had fewer than 6 days cited. A summary is shown in Table 4, and an accompanying histogram appears in Figure 1.

TABLE 4. EXTERNAL ENVIRONMENTAL FACTORS				
Factor	Mean	Median	Standard Deviation	
Weather (days lost)	20.32	12	21.95	
Security Incidents (days lost)	5.32	3	6.08	
Other External Environmental Issues (days lost)	6.60	1	11.70	



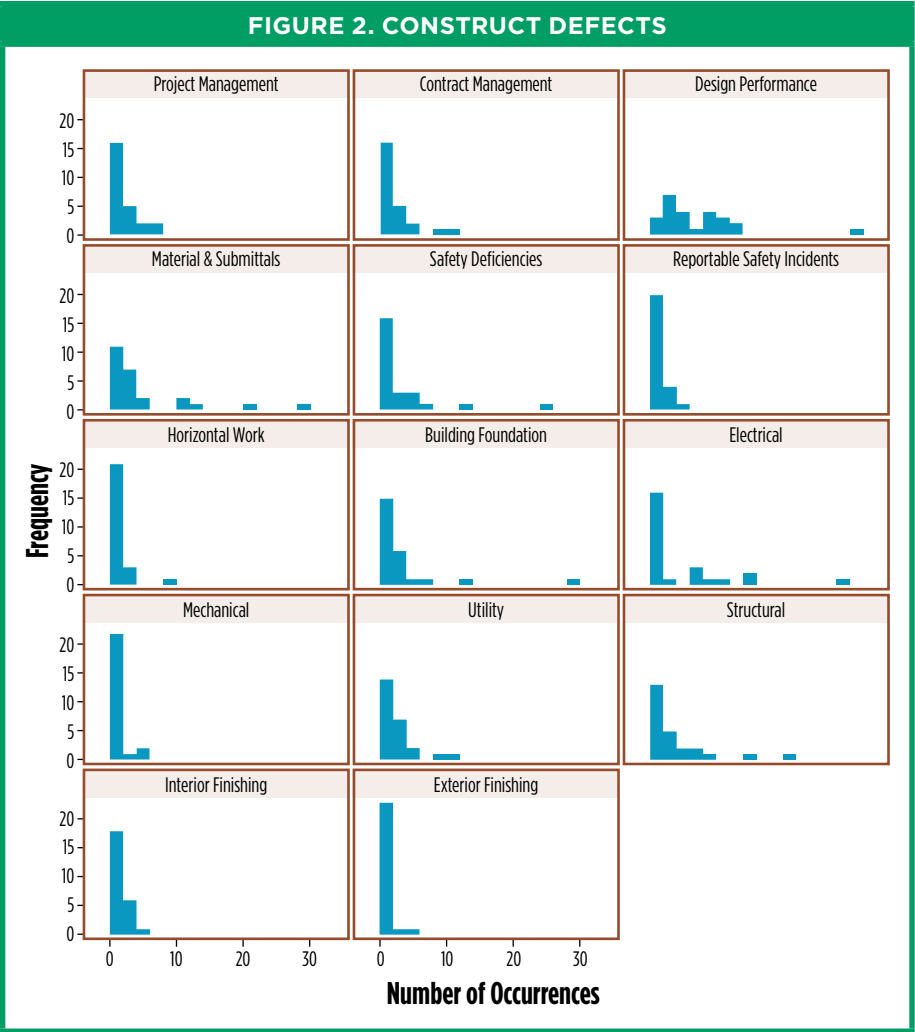
Significant variance in the number of quality deficiencies was also noted among the projects. The most common performance problems were with the design and material submittals of a project. There were no recorded incidents of poor engineering that led to a failure. However, because the government had a thorough review process, the most commonly observed problem was contractors submitting finalized designs that did not address all the review comments, causing many unnecessary revision and resubmission cycles. The majority of projects had between 0 and 15 design performance incidents, and one project had 31. For material and submittal deficiencies, contractors were often late in submitting material submittals, and they also commonly ordered materials that did not coincide with the original submittal. However, most projects maintained an incident rate

of five or less, with three projects being above that, and one as high as 24. The material submittal incidents were slightly more normally distributed (90 percent between 0 and 20), and the highest count was 28 incidents.

Of the eight quality factors, four had significant variance. The most common quality problem was Electrical work (both high and low voltage;  $M = 4.0$ ,  $SD = 6.72$ ). The project with the most Electrical problems had 28 recorded incidents. Structural issues were reported second most commonly ( $M = 3.0$ ,  $SD = 4.85$ ). The projects with the most Structural issues had 14 and 20 incidents respectively. Most projects did not have many Building Foundation problems ( $M = 2.7$ ,  $SD = 5.8$ ), but two projects had 12 and 28 each. Lastly, Utility issues ( $M = 1.7$ ,  $SD = 2.72$ ) had two outliers with 8 and 11 incidents. A summary of project performance is provided in Table 5, and an accompanying histogram is shown in Figure 2.

**TABLE 5. PROJECT DEFICIENCY SUMMARY**

<b>Deficiencies (No. of Occurrences)</b>	<b>Mean</b>	<b>Median</b>	<b>Standard Deviation</b>
Project Management	1.37	0	2.06
Contract Management	1.70	0	2.75
Design Performance	6.52	5	6.51
Material & Submittals	4.07	2	4.95
Safety Deficiencies	2.56	1	5.22
Reportable Safety Incidents	0.76	0	1.33
Horizontal Work	0.78	0	1.90
Building Foundation	2.70	1	5.77
Electrical	4.00	1	6.72
Mechanical	0.52	0	0.90
Utility	1.74	1	2.72
Structural	3.00	1	4.85
Interior Finishing	0.85	0	1.37
Exterior Finishing	0.48	0	0.56



# Results

The study used the Mann-Whitney pairwise comparison test with a 2-sided, normal approximation to test the research questions. The results, shown in Table 6, indicate that there are five significant factors and one near-significant factor that displayed differences across contract types. The *U* value is the rank assigned to the variable; the *z* is the test statistic value; and the “Sig. (2-tailed)” is the *p*-value for the test. Factors were determined



to be significant if they possessed a  $p$ -value of 0.05 or less. The Final Cost, Awarded Cost Growth, Final Period of Performance, Design Performance, and Contract Management were significant as a result of contract type.

**TABLE 6. MANN-WHITNEY TEST FOR CONTRACT TYPES**

Factor	Type	Mean	Standard Deviation	S	Z	Prob > Z
Award Amount	CPFF	\$25.6 M	\$17.6 M	125	-0.96	0.338
	FFP	\$25.3 M	\$26.4 M			
Final Cost	CPFF	\$37.5 M	\$28.6 M	105	-2.05	0.040*
	FFP	\$27.7	\$29.1 M			
Awarded Cost Growth	CPFF	1.48	0.38	98	-2.44	0.015*
	FFP	1.13	0.17			
Number of Contract Modifications	CPFF	10.1	4.8	124	-1.02	0.308
	FFP	7.4	1.8			
Change Orders	CPFF	3.4	2.8	120	-1.26	0.208
	FFP	2.1	1.4			
Number of FPOP <sup>7</sup> Extensions	CPFF	5.4	2.4	103.5	-2.17	0.030*
	FFP	3.3	1.3			
Total Days Added to Contract	CPFF	591	275	97	-2.49	0.013*
	FFP	330	151			
Initial Period of Performance	CPFF	390	145	138.5	-0.22	0.827
	FFP	373	145			
Final Period of Performance	CPFF	945	400	105	-2.05	0.040*
	FFP	668	209			
Awarded Schedule Growth	CPFF	2.46	0.77	107	-1.94	0.052 <sup>2</sup>
	FFP	1.86	0.61			
Security Incidents	CPFF	4.1	4.5	157	0.74	0.457
	FFP	6.9	7.3			
Other External Environmental Issues	CPFF	5.4	8.9	151.5	0.45	0.653
	FFP	8.2	14.4			
Weather	CPFF	22.9	22.4	126.5	-0.88	0.380
	FFP	17.1	2.1			
Project Management	CPFF	1.3	2.1	154	0.63	0.526
	FFP	1.6	2.2			
Contract Management	CPFF	1.2	2.8	180.5	2.15	0.031*
	FFP	2.6	2.7			
Design Performance	CPFF	3.9	2.7	187	2.39	0.017*
	FFP	10.1	8.2			
Material & Submittals	CPFF	6.1	8.5	119	-1.32	0.186
	FFP	2.3	3.7			

TABLE 6, CONTINUED						
Factor	Type	Mean	Standard Deviation	S	Z	Prob > Z
Safety Deficiencies	CPFF FFP	1.9 3.9	3.4 7.0	157.5	0.80	0.425
Reportable Safety Incidents	CPFF FFP	0.7 0.8	1.0 1.7	135	-0.48	0.631
Horizontal Work	CPFF FFP	0.6 1.2	0.9 2.8	140	-0.17	0.868
Building Foundation	CPFF FFP	2.1 4.0	3.2 8.1	151.5	0.45	0.652
Electrical	CPFF FFP	3.4 5.0	4.6 9.1	132.5	-0.58	0.561
Mechanical	CPFF FFP	0.5 0.6	1.2 1.2	152.5	0.62	0.531
Utility	CPFF FFP	1.7 2.1	2.9 2.6	150	0.37	0.709
Structural	CPFF FFP	3.2 3.4	5.3 4.5	149.5	0.33	0.738
Interior Finishing	CPFF FFP	0.6 1.3	1.0 1.7	156	0.77	0.438
Exterior finishing	CPFF FFP	0.6 0.5	1.2 0.5	151	0.48	0.628

Note.  
\*Signifies 2-tailed significance ( $p < 0.05$ ). Reject null hypothesis.  
<sup>1</sup>FPOP (Final Period of Performance)  
<sup>2</sup>Nearly significant; and is significant using Fisher’s Exact Test in a contingency table.

Final Cost for wartime projects was significantly lower for FFP contracts, as suggested by the literature. Likewise, Awarded Cost Growth was significantly lower for FFP contracts as well.

Final Period of Performance was lower for FFP contracts. The Awarded Schedule Growth Index was calculated by dividing the final government-allowed period of performance by initial contractual period of performance (not necessarily the actual performance period). The actual period of performance could not be used to calculate a schedule growth factor because of the inherent differences between fixed-price and reimbursable contracts. Fixed-price projects are contractually able to continue in operation after the contractual completion date has expired because the contractor is responsible for the risk. However, reimbursable contracts must be closed out when the period of performance expires unless the owner extends the

contractual completion date. Therefore, in a reimbursable contract, the actual completion date is always the same or before the contractual date. Consequently, actual completion dates are incomparable between the contract types. Thus, projects were compared using the contractual completion date. Moreover, the contractual completion date is within the control of the owner (whereas actual completion in fixed contracts is not) and is thereby a superior factor to compare between the two contract types. The Awarded Schedule Growth was a near-significant factor in the Mann-Whitney test. Therefore, further investigation was appropriate. A contingency table using Fisher's exact test revealed that Awarded Schedule Growth depended on contract type ( $p = 0.0154$ ).

The FFP contracts performed worse than CPFF contracts in terms of Design Performance and Contract Management, but not in as-built work. Contract Management was defined as the contractor's ability to fulfill the administrative requirements of the contract. Common deficiencies included missed schedule or status updates, or provision of adequate living and working conditions for the QA engineers. This finding suggests that while contractual requirements were not always met with FFP contracts, the finished facility was comparable to facilities constructed with CPFF contracts.

Project Management deficiencies were a separate construct than Contract Management, and significant differences were not found between contract types. Our definition of Project Management mirrors closely what Pinto and Winch (2016) describe as project delivery activities: planning, execution, controlling, and close-out. Examples of Project Management deficiencies included proceeding with work without approval or scheduling conflicting craft disciplines in the same work area, resulting in delays and worker conflicts. No Project Management differences were found between contract types.

Design Performance was carefully defined so that these issues did not overlap with Project or Contract Management. Therefore, these issues only included design quality and design schedule performance. Although the construction agent has identified several design flaws postcontract completion, no occurrences of construction failure were recorded as a result of poor design. The most frequently observed Design Performance deficiency was late design submissions, and the responses to these issues were different across contract types. These late submissions caused FFP contractors to work at risk. Working at risk occurs when designs are not approved by the owner and the contractor decides to continue with construction, knowing rework may occur if the design changes before it is approved. This rework

is not compensated by the owner. The results suggested that FFP contractors were willing to accept this risk to stay on schedule and to avoid contractual penalties. On the other hand, the CPFF contractors did not have as many instances of Design Performance deficiencies. This significant difference suggests that the contractors were likely not motivated to work at risk because fixed profits were guaranteed and they did not fear the accompanying schedule growth.

***Reimbursable contracts were found to have significantly higher costs than fixed price contracts. This difference was found for cost increases during the life of the project and the final project cost.***

## Discussion

### Cost

Reimbursable contracts were found to have significantly higher costs than fixed price contracts. This difference was found for cost increases during the life of the project and the final project cost. Notably, there was not a significant difference in Award Amount between contract types. These findings demonstrate that reimbursable contracts are likely to be awarded at similar prices to FFP contracts, but are likely to cost more at the end of the project. The validity of this conclusion is strengthened by the significant difference seen in cost growth. In the analysis, large projects were compared alongside small projects; and there may have been considerable variance between the project factors, which may reduce the credibility of a direct comparison in terms of raw cost or some other attribute. The Awarded Cost Growth Index standardizes the projects' cost comparisons. For example, larger projects may have differences in risk and nature of work than smaller projects. Additionally, when a larger project experiences delay, it ought to cost more money to make up the time deficit. The Awarded Cost Growth Index removes unique assignments of cost to enable comparisons. When this was done, we found that the ratio between final and initial costs is significantly higher for reimbursable contracts versus fixed-price contracts. Higher cost growth in reimbursable construction contracts aligns with other industry research. Reimbursable contracts do not incentivize cost control (Nkuah, 2006); rather they may incentivize cost growth (Wamuziri, 2013). Thus, as expected, wartime construction contracts exhibited the same cost behavior as peacetime contracts.

## Schedule

The average time required to complete a wartime reimbursable project is greater than the time for a fixed-price project. This is consistent with peacetime findings and confirms Jaszowskiak's (2012) results for other Afghan and Iraq U.S. military construction projects. The observed Awarded Schedule Growth is expected because structurally speaking, schedule and cost growth are strongly linked in reimbursable contracts. Whether funding becomes exhausted due to slow progress or unanticipated cost overruns, government contracting personnel are limited in their options for reimbursable contracts (assuming all costs have been legitimized during invoice auditing). To continue the project, they must provide additional funding, reduce the project scope, or terminate the contract in its current state (FAR, 2015, pts. 52.232–22). Based on this structural connection, we would expect contract modifications to be a mediating variable. Indeed, previous research has shown that contract changes are closely related to schedule performance in projects (Ibbs, 2011). While total number of Scope Changes was not different between the contract types, reimbursable contracts had more schedule modifications than fixed contracts. Additionally, the Total Days Added to the Contract was also higher for reimbursable contracts. Therefore, the results suggest that, rather than Scope Changes being the cause of Awarded Schedule Growth, as Ibbs (2011) suggested, it may be some other mediating factor (or possibly the contractor's lack of incentive to adhere to the schedule) that begets more Awarded Schedule Growth in reimbursable contracts.



Contract types also had a near-significant p-value for differences in the Awarded Schedule Growth Index. The p-value was so close to 0.05 (unlike any other factor) that additional analysis was performed for the factor. A contingency table showed that Awarded Schedule Growth could be dependent on contract type. Reimbursable contracts had higher Awarded Schedule Growth than fixed contracts. This reflects similar behavior as discussed with Final Cost: contractors for reimbursable contracts may not be motivated to control Awarded Schedule Growth (Nkuah, 2006). FFP contractors are incentivized to minimize construction costs and schedule, which involves indirect costs as the project is delayed. CPFF contractors do not have these inhibitions for either cost or schedule. The construction agent reported that contractors would often divide their original bid by the number of days in the period of performance to establish a daily burn rate. Often, the daily burn rate was maintained or exceeded. But just as often, the planned schedule was not met, and the allocated funds were exhausted before the project was complete. Therefore, when more time was granted to the project, additional funding had to be granted to complete the same project (L. Schoenenberger, personal communication, 2014). By design, CPFF projects have greater potential for Awarded Schedule Growth, and this research found that for this sample, on average they did exhibit more Awarded Schedule Growth, confirming previous literature.

## Quality

Fixed-price contracts underperformed compared to reimbursable contracts in Design Performance and Contract Management. The daily reports indicated that the majority of the reported design deficiencies were due to incomplete design submissions to the government. The incomplete designs created a rework/resubmission cycle. The contractors would choose to work at risk on the projects (sometimes for months)—beginning construction without final, approved designs—in order to meet contractual performance obligations. Similarly, the contractors frequently worked at risk as they tried to comply with contract management tasks. Contractors would miss submission deadlines and would have difficulty correcting the deficiency. However, the daily reports did not indicate that project quality was directly affected as a result of contractors working at risk. Acceptable designs or contract submissions were eventually submitted. The tests suggest that contractors did not pay as close attention to contract and design documents on fixed-price contracts. It is interesting that projects were able to continue successfully in spite of severely late design submissions and approvals. This may confirm previous research suggesting there are unnecessary steps in



the government design-review process, or that some details of design are not critical to project completion and simpler criteria may still yield a successful project (Blomberg, Cotelleso, Sitzabee, & Thal, 2013).

This study found no significant difference in quality performance between the two contract types. This conflicts with the peacetime expected outcome of quality differences. As there is a relationship between time, cost, and quality, perhaps the differences are manifest only in the observed time and cost growth. Our results also contrast with Jaskowski's (2012) work. Her survey of construction professionals found that a reimbursable project tended to yield better quality projects. This research did not find any craftsmanship quality differences between fixed price and reimbursable projects. These conflicting results may be attributable to the source of data. Jaskowski (2012) assessed overall perceptions from the government construction management teams, whereas this study's data consist of QA deficiency reports. This research did not analyze customer satisfaction of the project, which is a large consideration in determining the final quality of a project (Baccarini, 1999; Lim and Mohamed, 1999). Notwithstanding, this research suggests that heightened deficiencies or poor quality work should not be a unique subject of focus for either contract type.



## Security and the Environment

Reimbursable contracts are used in Afghanistan by the U.S. Government because of the increased risk due to the security situation. As a result, it was expected that external environmental factors would be more prevalent on reimbursable contracts. The use of this contract type is justified because of the more austere or uncertain project environments. However, there was no significant difference in delays due to any of the external environmental factors. In fact, security incidents and other external environmental delays (e.g., local interference) were reported more often in fixed-price contracts though not significantly. This result may suggest that risk assessments may not adequately assess the security situation for both reimbursable and fixed-price projects. Additionally, the term 'high risk' has a broad meaning. A project may have been high risk simply due to being in a remote location or



due to the security situation. Additionally, some accessible projects are classified as high risk because of the undefined scope, or anticipation of many change orders as the end-user firmed up requirements (L. Schoenenberger, personal communication, 2014). As the external environment was not a significant factor between contract types, these findings may also suggest that the high-risk projects are characterized more by vague project requirements than by the environment.

## Limitations and Conclusions

### Limitations

This study was limited to 25 projects, which restricted the statistical tests to nonparametric tests for the analysis. Future research should obtain a larger sample group, which will increase the number of analysis options. Another limitation was the depth of data retrieval from the daily reports. The combined length of the daily reports was approximately 20,000 pages. Therefore, only major deficiencies were analyzed. However, there were many other minor incidents recorded by the QA engineers. In-depth case study research on smaller groups of these projects may provide further insight into performance differences between contracts.

### Conclusions

The purpose of this research is to provide construction agents, firms, and military leaders alike with information that will aid strategic decisions regarding future military construction and nation-building projects. All of these facts underline the rapidly changing environment that is wartime construction, which has a significant effect on the progress of a project. The results largely confirm that which has been known for decades. FFP contracts achieve lower cost and schedule growth than CPFF contracts. Additionally, we found similar external risk profiles for both types of contracts. Both contract types faced similar austere conditions in terms of physical attacks and a harsh environment. Nevertheless, it would be irresponsible to assume that FFP contracts are more advantageous for the government to use in a wartime environment. There were specific reasons, usually risk-oriented, that led the construction agent to use CPFF contracts, especially in the initial stages of the Afghanistan reconstruction. Arguably, the use of CPFF may have prevented the default of contractors on more high-risk projects. Instead, the message of this article is that owners need to be aware that reimbursable projects are likely to have more cost and schedule growth. Owners and their agents need to take proactive steps to minimize the growth and to reduce construction inefficiencies.

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## Biographies



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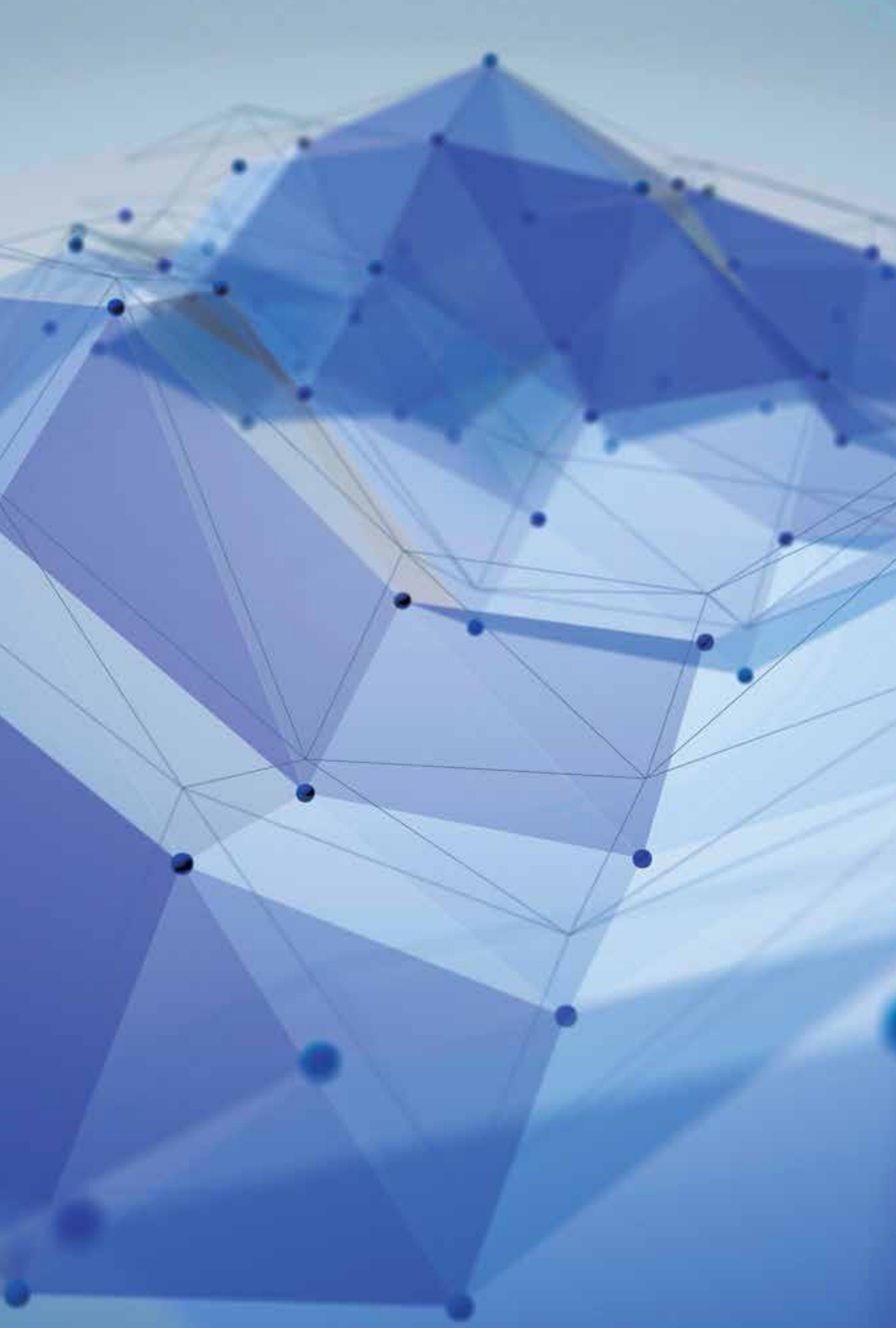
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## Featured Book

*Predator: The Secret Origins of the Drone Revolution*

**Author:** Richard Whittle

**Publisher:** Henry Holt & Company, L.L.C.

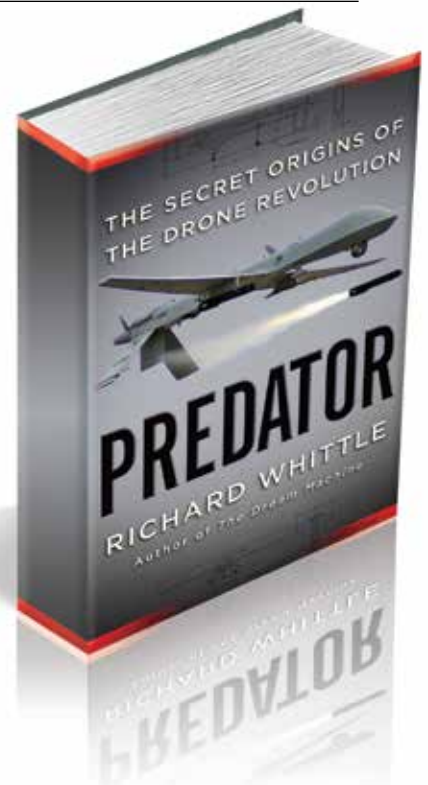
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**ISBN-13:** 978-0805099645

**Reviewed by:** Dr. Julien Demotes-Mainard,  
Senior Analyst, Avascent Europe,  
Paris Office





## Review:

Richard Whittle, a global fellow at the Woodrow Wilson International Center for Scholars, longtime military journalist, and author of *The Dream Machine: The Untold History of the Notorious V-22 Osprey* (reviewed in the *Defense ARJ*, Vol. 74, July 2015) continues his deep-dive investigation of high-profile weapon programs by this time unveiling the development of the Predator drone. Whittle has prepared the volume drawing on hundreds of interviews with program stakeholders, and 5 years of (obviously careful) research that eventually granted the author access to a myriad of supporting documents. Readers of the *Dream Machine*, accustomed to Richard Whittle's methodology and style, won't be disoriented by this new opus. *Predator's* narrative structure is essentially a reiteration of the previous V-22 saga: the author seeks to relate the individual fates, fortunate or unfortunate political decisions, military events, and operational anecdotes that shape the course of the MALE UAV (Medium-Altitude Long-Endurance Unmanned Aerial Vehicle) history, from its inception in the 70s, to Predator's armed debut after the 9/11 attacks.

In the introductory chapter, we learn that one of the most effective weapons in the current U.S. arsenal finds its origin in the aftermath of the Yom Kippur war, when a visionary Israeli engineer—Abraham Karem—pioneered the deployment of unmanned aircraft to collect and dispatch real-time tactical information on enemy positions. For acquisition students, the second (and central) part of the book, is undoubtedly the most interesting element of Whittle's examination. It describes how long-endurance UAVs first envisioned in the 80s as small, cheap observation tools, progressively turned into large and deadly platforms during the following decade. With a wealth of detail, the author recounts the technological hurdles drone supporters had to overcome during this 20-year development marathon (e.g., circumventing the issue of remotely piloted operations), as well as the evolution of military thinking and requirements that eventually led the Air Force leadership to weaponize the vehicle.

The book is superbly researched, well-structured, and easy to read. Whittle has an unquestionable talent for capturing his audience's attention through a compelling and thrilling story-telling. Readers less familiar with UAV jargon and airborne technology will certainly appreciate the effort put forth by the author into carefully explaining each key technological development (e.g., the installation and functioning of Hellfire payload) in a clear and intelligible way.

In sum, this volume is a worthwhile read for anyone interested in better comprehending the development of Predator, and the subsequent mass adoption of MALE UAVs. However, beyond the usual “bureaucratic road-block” and “inter-Service rivalry” arguments, it only adds marginally to our understanding of the weapon systems acquisition process. Fair to say, Whittle shows here no intention to deviate into this type of analysis, but as such, his last opus might nonetheless present a more limited interest for those seeking to extrapolate broader conclusions on how DoD and its armed forces procure the weapons they need.

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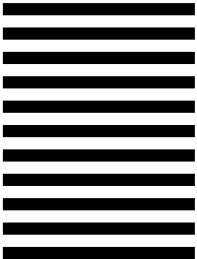
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